2020-08

Impact of climate change on groundwater recharge in lake Manyara catchment

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IMPACT OF CLIMATE CHANGE ON GROUNDWATER RECHARGE IN LAKE MANYARA CATCHMENT

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A Dissertation Submitted in Partial Fulfillment of the Requirements for the Degree of Master's in Hydrology and Water Resource Engineering at Nelson Mandela African Institution of Science and Technology

Arusha, Tanzania

August, 2020

ABSTRACT

This study aimed to estimate the groundwater recharge of the Lake Manyara catchment (7920 km^2) in two different time intervals, historical 1988-2018 and near-future 2021-2050 climatic condition. This study analyzed the trends, spatio-temporal variability in rainfall and temperature, and the length of the rainy season (LRS) in the Lake Manyara catchment, Tanzania covering a period between 1988 and 2018 using stations and satellite climate product. The Mann-Kendall statistical test, Sen's slope estimator and inverse distance weighting interpolation techniques were used to detect the trends, magnitude of trends and spatial distribution of rainfall and temperature. A modified Stern's method and water balance concept were used for rainfall onset, cessation and LRS analysis while standardized precipitation index (SPI) was used to investigate the wetness or dryness of the area. Then Coordinated Regional Downscaling Experiment output (CORDEX) Africa data rainfall and temperature projections obtained and lastly used as input data in the WetSpass model for groundwater recharge estimation. The results showed high variability and decreasing trends (4 mm/y) in annual rainfall and non-significant increasing trend for minimum and maximum temperature. The WetSpass results showed historical mean annual recharge of the catchment was 53.9 mm/y with the potential groundwater recharge of 149 Million Cubic Metre (MCM). The results of projected recharge estimated to be 88.5 mm/y with the potential groundwater recharge of 421 MCM. Statistically the contribution of the historical rainfall to the groundwater recharge was 6.7% compared to 8.1% in the projected period. However, the most potential recharge zones in the catchment identified around the northern part (around Ngorongoro), western and southwestern (Buger ward and Mbulu). There is a need, therefore, for adaptation measures such as improving water productivity and irrigation at the farm and catchment level.

DECLARATION

I, Latifa Omary, with my signature below I hereby declare to the Senate of the Nelson Mandela African Institution of Science and Technology that this dissertation report is my own work and has never been submitted to any other university for the award of similar or other degrees. I have followed all instructions in ethical and technical principles of scholarship in the preparation, data collection, data analysis and compilation of this Dissertation.

Latifa Omary

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Name and signature of candidate **Date**

The above declaration is confirmed

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Name and signature of supervisor 1 **Date**

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Name and signature of supervisor 2 **Date**

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CERTIFICATION

The undersigned certify to have read and accepted this dissertation titled "Impact of climate change on groundwater at Lake Manyara catchment, Tanzania", to fulfil the requirements for Master of Hydrology and Water Resource Engineering (Hydrology and climate studies) of the Nelson Mandela African Institution of Science and Technology (NM-AIST).

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ACKNOWLEDGEMENTS

First and foremost, I thank God for his protection, strength, patience and good health throughout the entire period of my studies and the successful completion of this program. I would like to express my gratitude to my first supervisor Late Professor Alfred N. N. Muzuka, who died in the mid-August. Our Almighty God may continue to rest his soul in peace. I would like to appreciate his constructive idea towards this study from the concept note up to the end of the research. Unfortunately, God loves him more than us. I will never forget the assistance and valuable guidance he gave me toward the accomplishment of this research. Also, I would like to appreciate my new supervisor's Dr. Mwemezi Rwiza and Dr. Juma Rajabu for their support and assistant towards this study.

Other special thanks to my fellow's Dr. Isaac Laarbi, Mr. Mohamed Mwabumba, Mr. Gustavio Okwir and my fellow students for their assistance and cooperation towards this present study. Other special thanks are directed to the Tanzania Wildlife Research Institute (TAWIRI) for allowing me to do research in the conservation area by providing entrance permit and collect data and reconnaissance survey in the study area.

I would like to express the deepest gratitude to Water Infrastructure and Sustainable Energy (WISE) Future for financial support for this study and Nelson Mandela Institution of Science and Technology for being among the selected student pursued Masters in Hydrology and Water Resource Engineering (Specialization Hydrology and Climate Studies).

I also acknowledge my employer, the Tanzania Meteorological Authority (TMA) for granting me study leave and Meteorological data for this research. Special thanks to the TMA's Director-General, Dr. Agnes Kijazi and the Director of research and Applied Meteorology Dr. Ladislaus Chang'a for their support during the study.

DEDICATION

This work is dedicated to my beloved parents Omary Nyembo and Ashura Mtawa who raised me and gave their special care during my entire childhood’s life and to my beloved daughter Moreen Patrick for their patience and support for the whole period of my studies.

TABLE OF CONTENTS

ABSTRACT i

DECLARATION ii

COPYRIGHT iii

CERTIFICATION iv

ACKNOWLEDGEMENTS v

DEDICATION vi

TABLE OF CONTENTS vii

LIST OF TABLES xi

LIST OF FIGURES xii

LIST OF APPENDICES xiv

LIST OF ABBREVIATIONS AND SYMBOLS xv

CHAPTER ONE 1

INTRODUCTION 1

1.1 Background of the Problem 1

1.2 Statement of the Problem 3

1.3 Rationale of the Study 4

1.4 Objectives of the Study 4

1.4.1 General Objective 4

1.4.2 Specific Objectives 4

1.5 Research Questions 4

1.6 Significance of the Study 5

1.7 Delineation of the Study 5

CHAPTER TWO 6

LITERATURE REVIEW 6

2.1 An overview of Climate Change and Variability Impact on Groundwater Recharge 6

2.1.1 Global Climate Change and Variability Trends 6

2.1.2 Climate Change and Variability in Tanzania 6

2.2 Hydrological Cycle and Water Resource 7

2.2.1 Groundwater Recharge 7

2.1.2 Groundwater Modelling 8

2.3 Impact of Climate Change on Groundwater 9

2.4 WetSpass Model for Groundwater Recharge 10

2.5 Conceptual Framework 11

CHAPTER THREE 13

MATERIALS AND METHODS 13

3.1 Study Area Description 13

3.2 Data Availability 14

3.2.1 Meteorological and Hydrological Data 14

3.2.2 Physical Data availability 16

3.3 Methods 16

3.3.1 Rainfall and Temperature Trends and Magnitude Detection 1988-2018 17

3.3.2 Future Scenarios Data 2020-2050 20

3.3.3 Groundwater Modelling 21

CHAPTER FOUR 31

RESULTS AND DISCUSSION 31

4.1 Spatial and Temporal Distribution of Rainfall and Temperature 31

4.1.1 Monthly Mean Rainfall and Temperature 31

4.1.2 Spatial-temporal Variability of Rainfall and Temperature 32

4.1.3 Mann–Kendall Trend Test of Annual Rainfall and Temperature 37

4.1.4 SPI Analysis of Rainfall 38

4.1.5 Rainfall onset, cessation and length of the rainy season 39

4.2 Future Climate Projections 41

4.2.1 Observed and Projected Monthly Average Rainfall and Trend 2021-2050 41

4.2.2 Projected Temperature Monthly and Trend 2021-2050 44

4.2.3 Projected Potential Evapotranspiration (PET) 46

4.3 Water Balance Estimation Outputs from WetSpass 47

4.3.1 Surface Runoff 47

4.3.2 Evapotranspiration 48

4.3.3 Recharge 49

4.4 Groundwater Potential Recharge Zones 50

4.5 Discussion 51

CHAPTER FIVE 53

CONCLUSION AND RECOMMENDATIONS 53

5.1 Conclusion 53

5.2 Recommendations...53

REFERENCES 55

APPENDICES 64

RESEARCH OUTPUT...69

LIST OF TABLES

Table 1: List of meteorological stations whose data (1988 – 2018) were used in the present study...15

Table 2: Classification scale of Standardized Precipitation Index[a] 19

Table 3: Characteristics of the Ensemble models of the CORDEX 21

Table 4: Land-use type and area coverage in Lake Manyara catchment 28

Table 5: Soil type and area coverage in the Lake Manyara catchment (FAO).....................29

Table 6: List of Man Kendal and Sen's slope result for annual (a) Rainfall (b) Maximum temperature (c) Minimum temperature 38

Table 7: Classification of the Standardized Precipitation Index and the corresponding number of years from 1988-2018 39

Table 8: Onset and cessation patterns of rainfall for 30 years in Lake Manyara Catchment from 1988-2018 40

Table 9: Water balance components for historical 1988-2018 and projected 2021-2050 of the Lake Manyara catchment...50

LIST OF FIGURES

Figure1: Schematic representation of the input data in the WetSpass model 12

Figure 2: (a) A map of Tanzania indicating (b) study area (c) Lake Manyara catchment 14

Figure 3: Hypothetical raster cell representation of water balance (Batelaan & De Smedt, 2001) 23

Figure 4: Mean monthly cycle of rainfall (a-c), maximum temperature (d-f) and minimum temperature (g-i) for Babati (a, d, g), Monduli (b, e, h), and Mbulu District office (c, f, i) from 1988-2018 32

Figure 5: Annual rainfall for (a) Babati (b) Monduli (c) Mbulu District Office (d) Arithmetic mean of the catchment 1988-2018 33

Figure 6: Annual rainfall patterns for the arithmetic mean of stations in east, south and west part of the Lake Manyara catchment from 1988-2018 34

Figure 7: Spatial distribution of mean annual rainfall for the period 1988 to 2018 in Lake Manyara catchment...35

Figure 8: Spatial distribution of mean annual (a) Maximum temperature (b) Minimum temperature for the period 1988 to 2018 35

Figure 9: The annual maximum temperature for (a) Babati (b) Monduli (c) Mbulu District Office (d) Arithmetic mean of the catchment and annual maximum temperature of (e) Babati (f) Monduli (g) Mbulu District Office (h) Arithmetic mean of the minimum temperature of the catchment from 1988-2018 36

Figure 10: Length of seasonal rainfall in days (a) Karatu Agric (b) Babati (c) Monduli (d) Mbulu district..41

Figure 11: Projected and observed of monthly rainfall at (a) Babati (b) Monduli (c) Mbulu District (d) Karatu Agric from 2021-2050, and (d) Arithmetic mean of the whole catchment 43

Figure 12: Projected annual rainfall trend at (a) Babati (b) Monduli (c) Mbulu District office (d) Arithmetic mean of the whole catchment from 2021-2050...............44

Figure 13: Projected and observed mean temperature at (a) Babati (b) Monduli (c) Mbulu District office (d) Arithmetic mean of the whole catchment.............................45

Figure 14: Projected annual trend mean temperature at (a) Babati (b) Monduli (c) Mbulu District office (d) Arithmetic mean of the whole catchment from 2021-2050..46

Figure 15: (a) Current rainy season runoff (b) dry season runoff (c) projected rainy season runoff (d) projected dry season runoff 48

Figure 16: Evapotranspiration in Current rainy season (b) evapotranspiration in dry season (c) evapotranspiration in projected rainy season (d) evapotranspiration in the projected dry season...49

Figure 17: Current rainy season recharge (b) dry season recharge (c) projected rainy season recharge (d) projected dry season recharge..50

Figure 18: Groundwater potential recharge zones..51

LIST OF APPENDICES

Appendix 1: Rainfall, temperature and wind speed of the catchment 64

Appendix 2: Hydro meteorological parameter, elevation and slope....................................65

Appendix 3: Climatic projection inputs of (a) rainfall in rainy season (b) rainfall in dry season (c) temperature in rainy season (d) temperature in dry season (e) PET in the rainy season (f) PET dry season..66

Appendix 4: Spatial distribution of land use/cover in Lake Manyara catchment correct legend built up...67

Appendix 5: Spatial distribution of soil type in Lake Manyara catchment 68

LIST OF ABBREVIATIONS AND SYMBOLS

AE	Actual Evapotranspiration
ArcGIS	Aeronautical Reconnaissance Coverage Geographic Information System
ASCII	American Standard Code for Information Interchange
ASTER	Advanced Space borne Thermal Emission and Reflection Radiometer
CLM	Climate Limited- Area Modeling Community
CNRM	Centre National De Recherches Météorologiques, France
CORDEX	Coordinated Regional Climate Downscaling Experiment
COSMO	Consortium for Small-Scale Modeling
DEM	Digital Elevation Model
DMI	Denmark Meteorological Institute
DriC	Drought Indices Calculator
EC	European Commission
ESA	European Space Agency
GCM	Global Climatic Model
GHGs	Green House Gases
GIS	Geographic Information System
GMST	Global Mean Surface Temperature
GW	Groundwater
HIRLAM	High Resolution Limited Area Model
ICHEC	Irish Centre For High-End Computing
IDB	Internal Drainage Basin
IDW	Inverse Distance Weigh
IPCC	Inter-Governmental Panel for Climate Change
ITCZ	Intertropical Convergence Zone
JJAS	June July August September
KNMI	Konkinklijk Netherland Meteorological Institute
LaRC	Langley Research Center
LRS	Length of Rainfall Season
LU/LC	Land Use/Land Cover; describes the natural and human-made landscapes
MAM	March April May

MCM	Million Cubic Meters
MK	Mann-Kendall
MoW	Ministry of Water
MPI	Max Planck Institute of Meteorology
NASA	National Aeronautics and Space Administration
NM-AIST	Nelson Mandela Institution of Science and Technology
OND	October November December
PET	Potential Evapotranspiration
QGIS	Quantum Geographic Information System
RACM	Regional Atmospheric Climate Model
RCA4	Rossby Centre Regional Atmospheric Model
RCM	Regional Climatic Model
RCP	Representative Concentration Pathway
SMHI	Swedish Meteorological and Hydrological Institute
SPI	Standardized Precipitation Index
TAWIRI	Tanzania Wildlife Research Institute
TMA	Tanzania Meteorological Authority
USDA	United States Department of Agriculture
USGS	United States Geological Survey
WetSpass	Water and Energy Transfer Between Soil, Plants and Atmosphere Under Quasi-Steady State
WISE-Future	Water Infrastructure and Sustainable Energy Futures
WMO	World Meteorological Organization

CHAPTER ONE

INTRODUCTION

1.1 Background of the Problem

Climate variability and changes have been projected to increase by various climate-modelling systems (Olonscheck & Notz, 2017). These changes have been associated with an increase in anthropogenic greenhouse gases (GHGs) emissions from anthropogenic activities leading to global warming. The anthropogenic activities include industrial activities, bush burning, fossil fuel burning, usage of insecticide and pesticides (Pachauri *et al.*, 2014). These activities have contributed significantly to the increase in atmospheric concentrations of greenhouse gases since the 20th century (Solomon *et al.*, 2009). Undeniable evidence suggests that the impact of greenhouse gases on the earth's atmosphere is significant and inevitable (Hartmann *et al.*, 2017). The GHGs emissions impacts are associated with changes in climatic parameters such as temperature and rainfall. These changes may lead to catastrophic environmental and socioeconomic events including water scarcity, health problems, energy deficiencies, poor livelihoods, food insecurity, human insecurity, poor forestry practices, poor agricultural yields and low economic growth (Holman, 2005; Chang'a *et al.*, 2017). Rainfall and temperature changes result in large-scale changes in the hydrological cycle (Arreguín-Cortés & López-Pérez, 2013). Alteration of hydrological cycle affects significantly the availability and sustainability of surface water and groundwater resources especially on hydraulic characteristics, water levels and residence time (Dragoni & Sukhija, 2008; Brown *et al.*, 2009).

Many catchments in the developing country experienced a challenge to secure the sustainability of quality water for the growing socio-economic development activities at the same time, preserving the essential watershed ecosystems. Climate is one of the three main factors that threaten the sustainability of groundwater; other factors include policy and land use/cover. The higher the rainfall, the more water availability and the lower the rainfall, drought likely to happen and little water supply (Lalika *et al.*, 2015). Temperature influences the availability of water resource; for example, high temperature can increase evaporation and evapotranspiration, which can decrease the amount of water (Dillon, 2005).

In Sub-Sahara Africa, the majority leave without the accessibility of clean water and at the same time are more vulnerable to the anticipated changes and variability in climate. Climate dynamics affect the distribution of rain and temperature in which can change river flows and reduce rates of groundwater recharge. Recently, the groundwater (GW) has been the primary source of water for drinking and irrigation in low rainfall and semi-arid areas where temporal and spatial surface water sources are too limited due to changes in climate (Kemper, 2004). Climate is a very crucial factor in recharge of the groundwater apart from slope, soil and elevation (Konikow & Kendy, 2005) reliable rainfall amount, intensity and frequency play a significant role in groundwater recharge. Therefore, changes in rainfall frequency, intensity and patterns as well as temperature have the direct and indirect impact on groundwater resource.

Various studies reported that the decrease of mean annual rainfall contributes much of the reduction of groundwater recharge, especially in the semi-arid area (Cavé *et al.*, 2003). The decline of the groundwater recharge is due to various reasons, including the delaying response of groundwater to the saturated zones. The detection on the response of groundwater to climate change can takes days to ten years or more due to the groundwater-residence time that interrupts and disperses the effects of climate (Meerkhan, 2015). However, the modelling approaches can quickly detect the response of groundwater to climate change. In Tanzania, little has been done on the groundwater responses to climate change at the catchment scale due to data unavailability to many areas. Therefore, the model applications to study groundwater response to the climate change is inevitable in order to have spatial and temporal distribution of groundwater. Different studies proved the applicability of the Geographical Information System (GIS) based hydrological models, WetSpass in detecting the groundwater response to climate change in different parts of the globe, including sub-Sahara Africa (Gebremeskel, 2015; Meresa & Taye, 2019). The availability of GIS-based models like WetSpass provides a possibility of conducting the hydrological researches even in poorly gauged catchments through fundamentals processes in the hydrological cycle. Therefore, this study used WetSpass model in determining the impact of climate change on the groundwater in Lake Manayara catchment, Northern Tanzania.

Tanzania experiences a heterogeneous climate condition due to the complicated topographical patterns, numerous inland water bodies, variation in vegetation types and land-ocean contrasts (Kijazi & Reason, 2009). The complexity leads to the modification of climate among different areas even within a relatively small distance depending on the sensitivity of the hydrological response and processes towards the different geophysical feature of the area

(Karim *et al.*, 2016). Therefore, climatic change and variability highly announced in different parts of the country at different extent.

In Tanzania, some people use surface water, and others use groundwater resources for water supply. In the semi-arid area, the groundwater is used often due to limited surface water availability. Moreover, in these areas groundwater account for about 60 to 80% of water supply to the population for domestic and agriculture uses (Elisante & Muzuka, 2017). Groundwater resource is the only ideal solution of water use in the semi-arid area but still the number of aquifer exploration information poorly documented as the results the management of groundwater resource becomes a big challenge. Additionally, increasing climate change and complicated topographical systems might accelerate the impacts of climate change and variability on groundwater resource. Therefore, the study aimed to analyze the impact of climate change and variability on groundwater recharge at Lake Manyara catchment, which is very useful as inputs information for water resources management, adaptation and regional development.

1.2 Statement of the Problem

The Lake Manyara catchment is one of the sub-catchments within the Internal Drainage Basin (IDB) that supports rain-fed, irrigated agriculture, livestock and wildlife. Agriculture and tourism are the main economic activities and source of employment and income for people and nation as well in the catchment. Intensification of human activities and climate variability and change stresses intensify water use due to the increased freshwater demands and temporal variability of surface water flow. Unfortunately, the area seems to show drought signal at large during the dry seasons and decrease in precipitation in the wet season. In the catchment, water becomes the most vulnerable resource to the community as the result of conflict between pastoralists.

Various studies have been carried out (Chang'a *et al*., 2017; Kijazi & Reason, 2009; Lema & Majule, 2009; Zorita & Tilya, 2002) to examine the impact of climate change. However, these studies did not analyze the impact of climate change on groundwater recharge that is important for groundwater management plans. Therefore, there is a need for this study to examine the impact of changes in climate on the groundwater resources.

1.3 Rationale of the Study

Groundwater is one of the main reliable water resources in many areas of the world particularly semi-arid areas of sub-Saharan Africa where water resources depleted and become scarce mainly due to climate change. In this condition of depletion of water resources and climate change sustainable water resource management is essential and urgent. Moreover the development of sustainable water resource management plans need a good understanding of the available water resources, climate change and their interaction. This study analyses the impact of climate change on groundwater in Lake Manyara catchment to develop the required understating for the sustainable water resources in the area. Lake Manyara is one of the essential tourist site, which support the economy of the country and generate many employments due to attraction of the existing biodiversity overt the area. However, the sustainability of the Lake Manyara biodiversity and tourist attraction depend on availability of water resources. Therefore, this study is essential, as the output from this study would be used to develop water resources management policy frameworks and climate change adaptation plan at a catchment level.

1.4 Objectives of the Study

1.4.1 General Objective

To examine the impact of climate variability and climate change on groundwater recharge in the Lake Manyara catchment.

1.4.2 Specific Objectives

(i) To understand the changing patterns of the rainfall and temperature over the past years.

(ii) To assess the future climatic condition within the Lake Manyara catchment.

(iii) To understand the impact of climate change and variability on groundwater recharge and identification of potential recharge zones at Lake Manyara catchment.

1.5 Research Questions

(i) What are the present and future climatic conditions in the Lake Manyara catchment?

(ii) What are the spatial and temporal patterns of groundwater recharge in response to future climate change in the catchment?

(iii) What is the impact of climate change and variability on groundwater recharge and where are the potential recharge zones within the catchment?

1.6 Significance of the Study

Lake Manyara sub-basin is one of the essential tourist centres with economic potential as it generates income and provides employment. The implementation of these activities comes at an expense to water resources and recently, groundwater has become primary reliable water sources due to insufficiency of surface water resources resulted from population rise and climate change and variability stresses. In this regard, the mentioned economic activities depend on the availability of groundwater resources as adaptation measures to climate change. However, the sustainability of this groundwater resource depends on a good understanding of the factors influencing its availability in the catchment, including the potential impact of climate change. This understanding can lead to the development of appropriate mechanisms for groundwater resources assessment and management.

1.7 Delineation of the Study

Based on the site visit, topographical maps of the Internal Drainage Basin (IDB) and the application of Digital Elevation Model (DEM) in the GIS software; the study area were delianed from lake Manyara sub-basin into districts catchments including the study area (Lake Manyara catchment). The study analyses rainfall and temperature trends for Lake Manyara catchment for the historical (1988-2018) and near-future (2021-2050) periods. In the study, temporal and spatial pattern analysis for rainfall and temperature (Maximum and minimum) were performed. In addition, the study analyses the Specialized Precipitation Index to detect the occurrence the wetness or dryness in the study area. On the groundwater modelling, the study made an application of WETSPAS model to estimate recharge amount and identify recharge potential zones. This analysis also involved the impact of changes in climate parameters on the groundwater recharge amount to the study area. This study provide a useful information for water resource management policy framework and climate change adaptation plan for the study area and other areas with similar characteristics.

CHAPTER TWO

LITERATURE REVIEW

2.1 An Overview of Climate Change and Variability Impact on Groundwater Recharge

2.1.1 Global Climate Change and Variability Trends

Climate change is defined as changes and/or the variability of the mean properties of climatic variables persisting for a prolonged period, which could last for decades or longer. Such changes may be due to natural variability and/or human activity (Abolverdi *et al.*, 2016). According to the Intergovernmental Panel on Climate Change, the global mean surface temperature (GMST) for the decade 2006–2015 was 0.87 °C higher than the average over the 1850–1900 period (IPCC, 2018). Also, general changing pattern of precipitation observed globally including; (a) increased precipitation in high latitudes (Northern hemisphere) (b) reduction in precipitation in China, Australia and the Small Island States in the Pacific; and (c) increased variance in equatorial regions (Abolverdi *et al.*, 2016). These trends have led to alteration of the hydrological cycle that in turn affects the availability of water resources which already observed in the dry areas (Delgado *et al.*, 2010).

2.1.2 Climate Change and Variability in Tanzania

According to the National Climate Change Strategy (2012), some of the areas including northern highlands will continue to be affected by declining rainfall, frequent droughts and significant increases in spatial and temporal variability of rainfall (Chris, 2016). Moreover, the average annual temperature is projected to increase by 1.0 to 2.7 °C by the 2060s and by 1.5 to 4.5 °C by the 2090s (Action, 2017). Hot days and nights are much more pronounced in the areas as shown by various studies. Heavy storms also are projected to increase and hence affecting the hydrological cycle in one way or another (Jack, 2010). In Tanzania, especially semi-arid areas mostly found in Central and Northern Zones use groundwater resources for daily activities (Elisante & Muzuka, 2017). The areas are more vulnerable to the projections of the increase in frequency and intensities of extreme climatic events such as droughts and floods are expected over the semi-arid regions of Tanzania (Luhunga *et al.*, 2018). Several studies on climate change have been done in Tanzania (Zorita & Tilya, 2002; Kijazi & Reason, 2009; Luhunga *et al.*, 2014; Luhunga *et al.*, 2018) however, few studies have analysed the climate change at the local scale. Different studies have improved the understanding of climate change at the local level; however, researching how climate change impacts the hydrological patterns is still a challenge due to lack of hydrological data (Xu *et al.*, 2005; Fowler *et al.*, 2007). For sustainable water resources management, there is a strong need to understand the climate variability and changes at local scale and determine its impact on hydrology and water resources.

2.2 Hydrological Cycle and Water Resource

The hydrologic cycle is the conceptual model of cyclic movement of water between the biosphere, atmosphere, lithosphere and hydrosphere. Water in this world exists in different reservoirs including atmosphere, oceans, lakes, rivers, soils, glaciers, snowfields and groundwater. Water moves from one reservoir to another through processes like evaporation, condensation, precipitation, deposition, runoff, infiltration, sublimation, transpiration, melting and groundwater flow. The cycle has no exactly initial point but is believed to begin in the ocean where most of the water exists. The sun as a primary driver of the water cycle, it enables water to change from different processes and state to another through changes in temperature (Chan *et al.,* 2016).

After the sun heats water, some evaporate into the air and formulate cloud for precipitation. Some precipitation may fall as snow and can accumulate as ice caps and glaciers that can store frozen water for thousands of years. Snowpack's in warmer climates often thaw and melt when spring arrives, and the melted water flows overland as snowmelt. Once the precipitation hits the land surface, some water can either flow on the surface of the earth as surface run-off or infiltrate into the ground as groundwater. Some of the precipitation soaks into the ground and this is the primary source of the formation of the waters found on land - rivers, lakes, groundwater and glaciers. Some of the underground water is trapped between rock or clay layers this is called groundwater (Meerkhan, 2015).

2.2.1 Groundwater Recharge

Groundwater is the water stored beneath the earth's surface in soil and porous rock aquifers accounts for as much as 33% of total water withdrawals worldwide (Siebert *et al.,* 2010). According to Alley *et al.* (2002) about two billion people rely on groundwater as their primary water source while half or more of the water used for irrigation originates from groundwater (Siebert *et al.,* 2010). Groundwater also acts as the reservoir in dry seasons especially during prolonged dry seasons. Like money in the bank, groundwater sustains societies through the underground storage capability. Groundwater recharge in a broad sense is an addition of water to a groundwater reservoir. Groundwater recharge estimation is essential for the efficient and sustainable management of groundwater systems. Primary sources of recharge are rainfall, surface water bodies (ephemeral or seasonal rivers, lakes, estuaries) and irrigation losses. For estimating groundwater recharge, a variety of methods exists.

Different techniques have been used to estimate recharge amount in the region depends on different factors, including data availability and simplicity of the method. A different approach considers precipitation amount, soil moisture content, geological formation, soil properties, depth of water table and aquifer properties, vegetation, land use, topography and land slope (Obuobie, 2008). Consideration of these characteristics is a prerequisite in groundwater recharge estimation. Groundwater recharge estimation method has been classified according to the hydrological zones from which recharge can be obtained, including from surface water, unsaturated zone and saturated zone. However, the identification of the groundwater recharge potential zones are still challenging due to data scarcity and technological gap (Hughes, 2004). Recently, the development of the modelling technique emerges as a solution for the identification of recharge zones and groundwater recharge estimations. Several studies (Yang *et al.*, 1999; Hughes, 2004; Pereira *et al.*, 2009) have applied the modelling techniques for recharge estimation at the regional and local level however, the groundwater recharge potential differs from one locality to another. This condition necessitates a need for determining recharge potential and recharge amount to catchment level, which was the basis of this study.

2.1.2 Groundwater Modelling

Hydrological models are the most recent technique used to estimate both surface and groundwater amount based on time series data from hours to years. Nowadays, the hydrological models are considered as an essential and necessary tool for water and environmental resource management. The hydrological modelling techniques are potential in predicting present and future groundwater in the groundwater systems (Obuobie, 2008). There are several categories of hydrological models based on their physical parameterization and model structure. The types of hydrological models include conceptual, distributed, undistributed or stochastic (Kollet & Maxwell, 2008). Nevertheless, the existence of several approaches in determining the groundwater recharge amount, such as physical techniques, tracers within each of the hydrologic zones, modelling is a simplified representation of the real-world system (Gull *et al.*, 2020).

The best model is the one that gives results close to reality with the use of least parameters. Usually, the hydrological model is among the trusted technique that offers approximately to the fact. The essential inputs required for many groundwater models are hydro-meteorological parameters, watershed characteristics like soil properties, vegetation cover, watershed topography, soil moisture content, attributes of groundwater aquifer are also considered (Behrangi *et al.*, 2008). Among the globally applied models for the groundwater recharge, WetSpass model plays a crucial role in estimating the recharge amount of groundwater resource. This model has a competitive advantage over many hydrological models it can simulate the recharge under the presence of a few amounts of data in the catchment. Also, several studies have reported that the results obtained from WetSpass model have a strong relationship with other model results simulated in different areas (Meresa & Taye, 2019).

2.3 Impact of Climate Change on Groundwater

Climate change and variability can affect groundwater resources in both water quality and quantity directly or indirectly. Various studies reported that human activities and climatic stresses as some of the main factors influencing the availability and sustainability of groundwater (Alley *et al.*, 2002; Brekke *et al.*, 2004). Although understanding the potential effects of climate variability and change on groundwater is more complicated compared to surface water. Though, the knowledge of the impact of climate variability and change on groundwater at the local scale is vital for the development of water resource management plans (Holman, 2006).

The direct impact of climate change on groundwater is in recharge rates, although little attention has been given (Cai & Ofterdinger, 2016). Since the rainfall is the primary source for the groundwater recharge hence, the consideration of rains in the quantification of groundwater recharge needed to take in the account. However, it is not easy to study the impact of climate change on groundwater using traditional methods due to the different scale studies. Therefore, a better option to explore the climate change impacts on the groundwater at different scales remains to be model simulations.

Models simulations are physical or mathematical simplifications of natural systems used for analyzing physical parameter data. It also describes equations of physical systems and techniques that provide a means for quantitative explorations or predictions that will help in decisions making (IPCC, 2013). Hierarchy of models ranging from simple, intermediate to comprehensive climate and earth system models have been used for climate change projections (IPCC, 2013). Climate models described in a wide variety and multiple formats in which the numerical representations of the earth's natural systems used to study how climate responds to changes in natural and human-induced perturbations (Moss, 2010).

These climate models help to project future impacts of climate change in the planetary system. Consequently, there are improvements to the climate models in time and space in prediction of future climate change impacts that may occur. Since the fourth IPCC assessment report, climate models have improved for future prediction and for studying preceding climatic situations (IPCC, 2013). Several studies have been done on climate change and its impact on water resources (Ge & Chaoying, 2001; Brouyère *et al.*, 2004); however, few studies have documented the climate change impact on groundwater resources at the catchment level (Brouyère *et al.*, 2004). Moreover, different characteristics exist in different catchment/locality, which leads to diverse impacts of climate change on groundwater resources. Therefore it is necessary to conduct various climate impact studies on the groundwater to different catchment, which is a focus of this study at lake Manyara.

2.4 WetSpass Model for Groundwater Recharge

WetSpass is an acronym which stands for water and energy transfer between soil, plants and atmosphere under quasi-steady-state (Batelaan & De Smedt, 2001; Batelaan & De Smedt, 2007). The inputs parameters include both physical and hydro-meteorological input files for the long-term average for simulation of spatial patterns of interception, surface runoff, actual evapotranspiration and groundwater recharge (Batelaan & De Smedt, 2001; Batelaan & De Smedt, 2007; Aish *et al.*, 2010). The model application embedded with the ArcGIS software in the simulation process. Different regions successfully use WetSpass in the estimation of seasonal and annual recharge and good results obtained. In WetSpass, the spatial distribution of water balance performed at raster level and the summation of individual raster water balance give independent water balances for the vegetated, bare soil, open- water, and the impervious fraction of a raster cell. Finally, the total water balance obtained after the summation of the water balance of each cell in the region (Al Kuisi & El-Naqa, 2013).

2.5 Conceptual Framework

In this study, WetSpass used to analyze the average groundwater recharge to the sensitivity of climate variability through sub-surface heterogeneity within the catchment. In Fig. 1, showed the schematic diagram of the inputs data in the WetSpass model. It is a physical based model for the estimation of long-term average spatial patterns of groundwater recharge, surface runoff and evapotranspiration by employing physical and empirical relationships. The model can predict hydrological processes at a seasonal and annual time step. The model also helps to identify the potential recharge zone for the sustainability of wells and proper protection of the aquifer zone for groundwater. From this study, potential groundwater recharge zones showed by using GIS-based method as the component in the WetSpass model. Various studies applied WetSpass in a different country for annual and seasonal groundwater spatial variation estimation, and the results were successfully estimated when compared to other methods (Al Kuisi & El-Naqa, 2013).

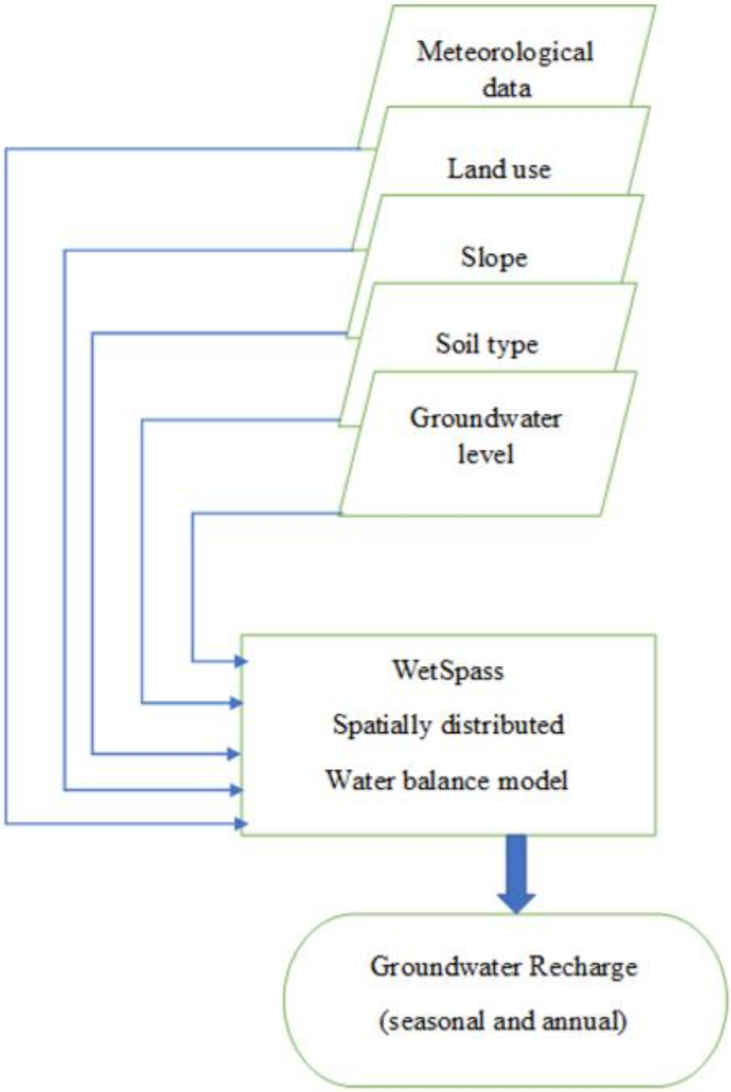

Figure 1: Schematic representation of the input data in the WetSpass model

CHAPTER THREE

MATERIALS AND METHODS

3.1 Study Area Description

Lake Manyara catchment is located within two regions, namely Arusha and Manyara, and five districts, which are Arusha, Babati, Monduli, Karatu and Mbulu. The Lake Manyara sub-basin comprises of three catchments namely, Lake Manyara, Lake Burunge and Lake Babati. This study was conducted in the Lake Manyara catchment (Fig. 2c), which is at the upper part of Lake Manyara sub-catchment with an area coverage of about 7920 km^2 (Attarzadeh *et al.*, 2015). It is located from latitude 3°00′ S to 5°30′ S and longitude 35°30' E to 37°00′ E (Fig. 2c). Lake Manyara has no outflow, no outlet to the sea or other lakes and believed to be very sensitive to climate and almost three-quarter of the lake falls within a conservation area (Olaka *et al.*, 2010).

Climatologically, the region characterized by bimodal rainy seasons with short rains between October and December and long rains between March and May, however, the southern part of the catchment is in the transition area with both unimodal (rain from November to April) and bimodal characteristics. The mean annual rainfall in the catchment is approximately 790 mm (Deus & Gloaguen, 2013; Bachofer *et al.*, 2014) with an annual mean temperature of 19.4 °C (Yanda & Madulu, 2005).

The most dominant types of land use and land cover in the Manyara catchment are bush land, woodland, grassland, cultivated land and bare soil (Maerker *et al.*, 2015). According to Ngana *et al.* (2003) during the dry season, herds of livestock migrate to the lake from other areas, thereby increasing pressure on the water resources at the catchment. Despite the pasture in the area, the most frequently cultivated crop types are bananas, maize, rice and vegetables (authors' observation) and most of the crops grown in this area have a high demand for water, and belongs to the group of the thirstiest crops (Lipper & Raney, 2007). Both perennial and non-perennial rivers bring water to the lake, but the main tributaries of Lake Manyara catchment are Mbu River, Simba River and Kirurumu River.

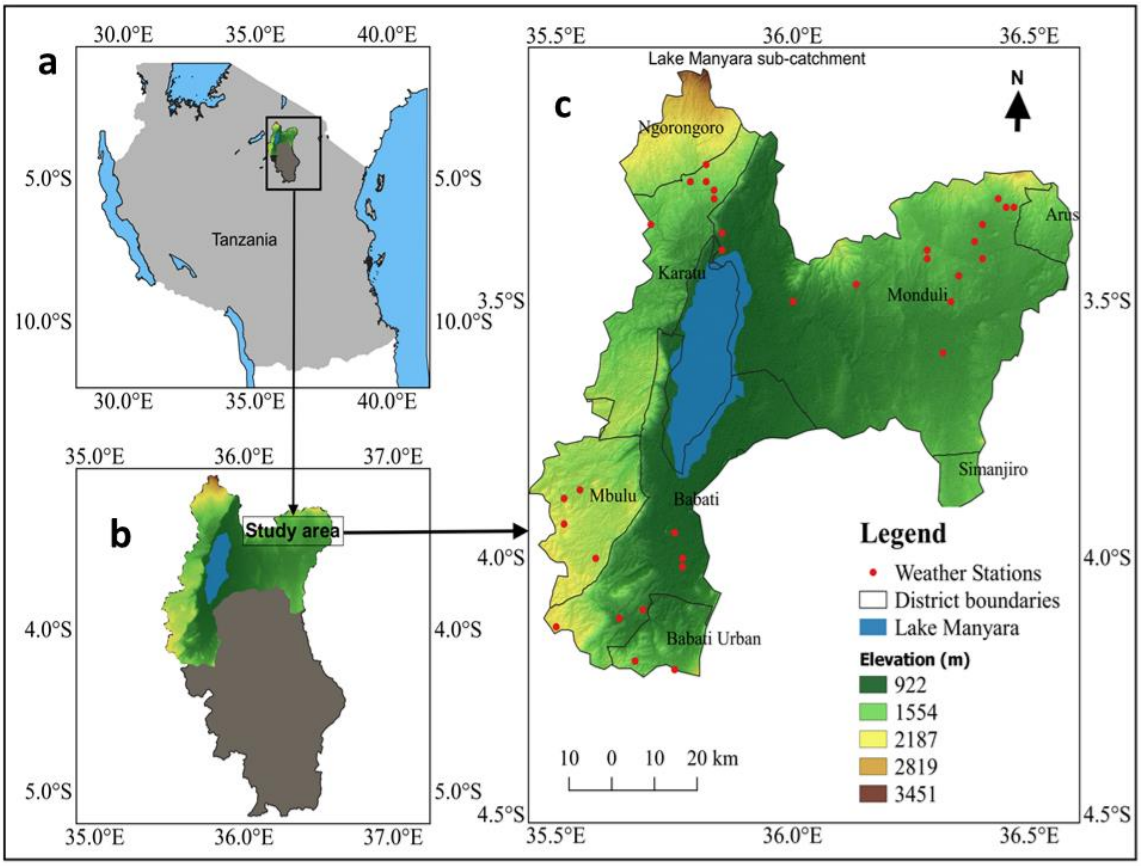

Figure 2: (a) A map of Tanzania indicating (b) Study area (c) Lake Manyara catchment

3.2 Data Availability

3.2.1 Meteorological and Hydrological Data

Daily rainfall and temperature data from 32 weather stations were used in this study (Table 1) however, only three stations (Mbulu District Office, Monduli and Babati) had observed data. The available rainfall data covering the period 1988 to 2018 were collected from the Tanzania Meteorological Authority (TMA). Due to the lack of observed stations data for the rest of the weather stations outlined in Table 1, satellite-based rainfall and temperature products for the same period were collected and utilized. The satellite-based rainfall and temperature data were obtained from the NASA Langley Research Center (LaRC) POWER project. The NASA POWER data has the ability in reproducing well the climate pattern of stations data have been previously demonstrated (Larbi *et al.*, 2018). All data were then quality controlled to check outliers and negative rainfall values. This accomplished by find the mean of the data sets at a particular time interval.

Data quality control checked up, and the missing observed rainfall values were filled with the satellite rainfall data (NASA). The parameters collected were daily rainfall, wind, minimum and maximum temperature for the period of 1988 to 2018. The data have a resolution of 50 km. Potential evapotranspiration calculated from the maximum and minimum temperature by using DriC software. Hydrological data was collected in the headquarters of the internal drainage basin office (IDB) for groundwater levels in wells and boreholes within the catchment. The merged climate dataset developed by blending the observed and satellite data.

Table 1: List of meteorological stations whose data (1988 – 2018) were used in the present study

No.	Station name	Station number	Longitude	Latitude	Elevation
1	Mbulu District Dffice	9335001	35.6	-3.9	1737
2	Kainam	9335009	35.5	-3.9	1881
3	Idulu Ginnery	9335011	35.8	-4.0	1005
4	Mbulumbulu	9335024	35.8	-3.3	1828
5	Mbulumbulu 111	9335026	35.8	-3.3	1549
6	Mbulumbulu iv	9335027	35.8	-3.3	1508
7	Mbulu devp farm	9335029	35.5	-3.9	1828
8	Mto wa Mbu Game Department	9335030	35.8	-3.3	1066
9	Mto wa mbu Agriculture office	9335032	35.9	-3.4	975
10	Lake Manyara Maji	9335034	35.9	-3.4	999
11	Karatu Agricultural	9335046	35.7	-3.4	999
12	Tarosero Estate	9336007	36.4	-3.3	1402
13	Rasharasha Estate	9336008	36.5	-3.3	1524
14	Monduli	9336014	36.5	-3.3	1585
15	Eluanata Dam	9336019	36.3	-3.4	1371
16	Ardai 1	9336022	36.4	-3.4	1371
17	Ardai 11	9336023	36.4	-3.5	1371
18	Ardai 111	9336024	36.3	-3.4	1371
19	Ardai iv	9336025	36.4	-3.4	1371
20	Ardai v	9336026	36.4	-3.4	1371
21	Ardai Ranch	9336043	36.3	-3.5	2658
22	Mayoka-moya	9336047	36	-3.5	1071
23	Mangola	9336050	36.3	-3.6	999
24	Lente Estate	9336063	36.1	-3.5	999
25	Singu Estates	9431002	35.7	-4.2	1737
26	Margaret Coffee Estates	9435009	35.6	-4.1	1365
27	Mbogo Estates	9435012	35.7	-4.1	1127
28	Dukumomaay	9435023	35.5	-4.1	2133
29	Magugu Primary School	9435029	35.8	-4.0	999
30	Babati	9435030	35.8	-4.2	999
31	Darakuta Ranch	9435033	35.6	-4	1128
32	Magugu Tpri	9435035	35.8	-4	999

3.2.2 Physical Data Availability

Several GIS-based data were required in hydrological modelling, including the Digital Elevation Model (DEM), Slope, Land Use/Land Cover (LULC) maps and soil texture. The DEM at 30 m resolution was downloaded from http://srtm.csi.cgiar.org/ SELECTION/ inputCoord.asp; The DEM data was used for the computation of the slope data required for the model used in present study. Land Use/Land Cover map of 20 m resolution from the Sentinel-2A, 1-year observation (December 2015 to December 2016) was downloaded from http://2016africalandcover20m.esrin.esa.int/ download.php; and soil texture type was obtained from http:// www.waterbase.org/ download_data.html.

3.3 Methods

The present study involves three phases; one was to analyze the current climate status of the catchment from 1988-2018, second was future projections of the catchment in the near future 2021-2050 and lastly hydrological modelling for groundwater recharge estimations. The climatic analysis consideration was given to the one that shows the corresponding relationship to the water resources. These climate analyses include annual trends, spatial distribution and temporal analysis, Standardized Precipitation Index (SPI) to identify drought indices and length of seasonal rainy. Downscaling of the near future climatic projections of the catchment from 2021-2050 followed. The future data were required as the inputs in the WetSpass model to estimate future recharge of the catchment.

In the case of groundwater, recharge estimation, WetSpass model employed in this present study. The model makes use of remote sensing and GIS fundamental technique in which the inputs data include meteorological data, topographical data and soil data to estimate recharge of groundwater. WetSpass model developed purposely for the temperate condition area whereby the dry and wet seasons used to provide annual recharge. As stated previously, Tanzania has intricate topographic patterns with complicated weather systems in both time and space. Moreover, the country experiencing about six months of the dry season and six months of the wet season in most of the area, however, some parts experience two rain seasons per year.

3.3.1 Rainfall and Temperature Trends and Magnitude Detection 1988-2018

(i) Mann-Kendal (MK) Statistical Test

An investigation of the annual and monthly series and trend analysis was performed for each station and for the entire catchment. The annual rainfall and temperature trends were computed using the Mann-Kendall (MK) statistical test at the confidence level of 95% (Yavuz & Erdoğan, 2011). The MK statistic tests for whether to accept the alternative hypothesis (*Ha*) which states the presence of a monotonic trend or to accept the null hypothesis (*Ho*) which states that no monotonic trend occurred were used. The approach has been suggested by the World Meteorological Organization (WMO) as the best approach to assess trends in environmental data time series (Huret & Legras, 2014). The method is simple, robust against outliers and can handle missing values (Gao *et al.*, 2017). The MK tests (Equation 1 to 4) calculate the slope of the line formed by plotting the variable of interest against time, but only considers the sign and not the magnitude of this slope. The MK statistic S is computed as follows:

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} \operatorname{sgn}(x_j - x_k) \tag{1}$$

where n is the number of the data point, x_j is the *jth* observation and *xi* is the *ith* observation where $j>i$. The *sgn(.)* can be estimated as

$$\operatorname{sgn}(x) = \begin{cases} +1 \dots \dots if \dots \dots \dots . . (x_j - x_k) > 0 \\ 0 \dots \dots \dots if \dots \dots \dots . . (x_j - x_k) = 0 \\ -1 \dots \dots . if \dots \dots \dots . . (x_j - x_k) < 0 \end{cases} \tag{2}$$

The normal approximation, *Z* statistics, is stated in Equation (3)

$$Var(\mathrm{S}) = \frac{n(n-1)(2n+5) - \sum_{i=1}^{m} t_i(t_i - 1)(2t_i + 5)}{18} \tag{3}$$

where t_i is the extent of any given tie. Σt_i denotes the summation over all ties and is only used if the data series contain tied values. The standard normal variate Z is calculated as indicated in Equation (4):

The trends significance is evaluated by calculating the statistic *sgn (x).* The scattering (variance) is estimated as:

$$Z = \begin{cases} \dfrac{S+1}{\sqrt{Var(S)}} if \rightarrow S > 0 \\ 0 \ldots \ldots \ldots . if \rightarrow S = 0 \\ \dfrac{S-1}{\sqrt{Var(S)}} if \rightarrow S < 0 \end{cases} \tag{4}$$

The trend is decreasing if Z is negative and increasing if Z is positive. H_0, the null hypothesis of no trend, is rejected if the absolute value of Z is greater than $Z1-\ \alpha/2$, where $Z1-\ \alpha/2$ is obtained from the standard normal cumulative distribution tables.

(ii) Sen's Slope Estimator

The Sen's slope estimator (Equations 5 and 6) was used to determine the magnitude of the trends after obtaining the direction of the trend with the Mann–Kendall test. The method uses a linear model to calculate the change of slope, and the variance of the residuals should be constant in time (Sen, 1968).

$$Q_i = \frac{(X_j - X_k)}{(j-k)} for\ all\ k < j\ and\ i = 1, .. N \tag{5}$$

$$Q_{med} = \begin{cases} Q\left[\dfrac{(n+1)}{2}\right], \text{where } N \text{ is odd} \\ Q\left(\dfrac{N}{2}\right) + Q\left[\dfrac{N+2}{2}\right], \text{where } N \text{ is even} \end{cases} \tag{6}$$

where Q is the slope and B is constant.

(iii) Spatial Distribution Analysis

In this study, the spatial distribution of weather stations, and the recorded non-spatial values (precipitation and temperature) were used. The Geographic Information System (QGIS) was used for the development of a spatial database, spatial processes, and geo-visualization of the results of the analysis. The averaged values of annual precipitation and temperature calculated over 30 years for a total of 32 weather stations were used as the input data in the QGIS software (Abolverdi *et al.*, 2016). This annual rainfall and temperature values were interpolated to show the spatial patterns of distribution within the catchment using the inverse distance weight (IDW) technique, as indicated in Equation (7).

$$w\,(d) = \frac{1}{d^p}, \qquad p > 0 \tag{7}$$

where p is the number of points, d is the distance between points, and w is the weighting function.

(iv) Rainfall Anomaly and LRS Analysis

An investigation of dry, normal and wet years in the Lake Manyara catchment was performed using the Standardized Precipitation Index (SPI) approach for the time intervals of 12 months as presented in scale of McKee *et al.* (1993). The equation to represent Standardized Precipitation Index (SPI) indicated at the equation below;

$$SPI = \frac{f(x) - \mu}{\sigma} \tag{8}$$

Where by SPI= standardized precipitation Index, $f(x)$=normalized value of measured series (Precipitation), μ = average value of normalised series σ = standard deviation of normalised series.

The classification scheme in Table 2, suggested by McKee *et al.* (1993) was used to determine wet or dry intensity over the study area.

Table 2: Classification scale of standardized precipitation Index

Classification	Values
Extremely wet	2.00 and more
Very wet	1.50 to 1.99
Moderately wet	1.00 to 1.49
Normal	-0.99 to 0.99
Moderately dry	-1.00 to -1.49

Very dry	-1.50 to -1.99
Extremely dry	- 2.00 and less

McKee *et al.* (1993)

(v) Onset and Cessation of the Seasonal Rainfall

The onset and cessation dates were computed for the Babati, Monduli, Karatu and Mbulu District office stations for each year based on a modified method defined by Stern *et al.* (1981). In the present study, the rainfall onset date is defined as the date with the total of at least 20 mm of rainfall within two consecutive days, in which the starting day must be wet (at least 0.85 mm rainfall recorded), followed by a no dry period of seven (7) or more consecutive days occurring in the following 30 days. The cessation date was computed based on the Instat© concept of the water balance (i.e. the first date the soil profile is empty after a given date) which is calculated for each year. The length of the rainy season (LRS) was then obtained from the difference between the rainfall onset and cessation date.

3.3.2 Future Scenarios Data 2020-2050

Future climatic data used in this study was obtained from the ensemble model downloaded at http://www.cordexesg.dmi.dk/esgf-web-fe/ Africa data sets. In this study, the Coordinated Regional Climate Downscaling Experiment (CORDEX) Africa simulated data from four regional climate models were used to obtain the future climatic data over the Lake Manyara catchment (Table 2). The simulated data used were for the historical period (1971-2005) and the near future (2021-2050) for representative concentration pathway (RCP 4.5 and RCP 8.5) scenario of climate change. The obtained data of the future climate of the Lake Manyara catchment were used as the inputs in the WetSpass model to estimate future groundwater recharge of the catchment.

Table 3: Characteristics of the Ensemble models of the CORDEX

No.	RCM	Model center	Short name of RCM	GCM
1	CLM com COSMO-CLM (CCLM4)	Climate Limited- Area Modelling (CLM) Community	CCLM4	MPI ICHEC CNRM
2	DMI HIRHAMS	Darmarks Meteorologiske Instut (DMI) Danmark	HIRHAMS	ICHEC
3	SMHI Rossby Atmosheric Climate Model (RCA4)	Sveriges Meteorologiske Och Hydrologisks Instut (SMHI) Sweden	RCA4	MPI ICHEC CNRM
4	KNMI Atmospheric Climate Models, version 2.2 (RACMO2.2T)	Konkinklijk Nederland Instituut (KNMI) Netherlands	RACMO2.2T	ICHEC

(Luhunga *et al.*, 2018)

3.3.3 Groundwater Modelling and WetSpass Model Description

WetSpass stands for Water and Energy Transfer between Soil, Plants and Atmosphere under quasi-steady State. The application of this model is compatible and integrated with ArcGIS software during the simulation process. The inputs required in asci formats from the spatial maps prepared from the averaged meteorological data in which interpolation by ArcGIS (version 10.5) were carried out. WetSpass model in the present study used long-term average climatic data 1988-2018, together with topography, land cover and soil map, to estimate average spatial patterns of surface run-off, actual evapotranspiration and groundwater recharge (Batelaan & De Smedt, 2001). In WetSpass, the spatial distribution of water balance performed at raster level (Fig. 3) and the summation of individual raster water balance gives independent water balances for the vegetated, bare soil, open- water and impervious fraction of a raster cell. The model needs, the rainy and summer spatial distribution maps for hydro-meteorological parameters, physical parameters and tables formats. The groundwater amount calculated for the rainy season and dry season (Batelaan & De Smedt, 2001).

The results consequently summed to obtain the annual values. The water balance computation performed at a raster cell level. Groundwater recharge obtained by summation of each raster of independent water balances for the vegetated, bare soil, open-water and impervious fraction. The total annual groundwater recharge amount of the Lake Manyara catchment calculated as the summation of the recharge in the rainy season and dry season of each raster cell. Finally, the model output gave the water balance components including the recharge, runoff, actual evapotranspiration and interception for rain season and dry season. The inputs data for WetSpass includes maps in ASCII files and table file format (Meresa & Taye, 2019).

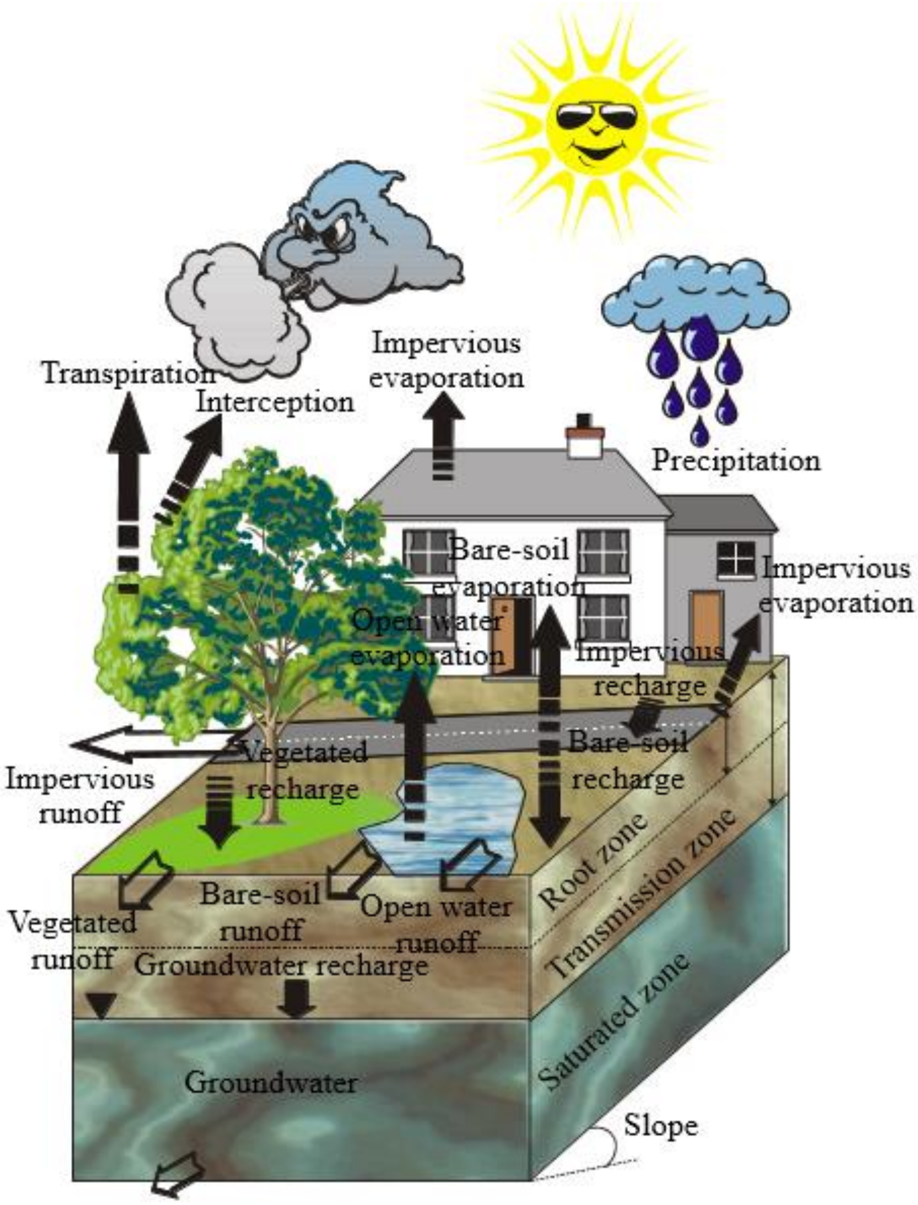

Figure 3: Hypothetical raster cell representation of water balance (Batelaan & De Smedt, 2001)

(i) Water Balance Calculation

The water balance components of vegetated, bare-soil, open water and impervious surfaces as indicated in Equations 9 to 11 were used to calculate the total water balance of a raster cell as follows:

$$ET_{raster=avET_v} + asE_s + aoE_{o+ai}E_i \tag{9}$$

$$S_{raster=avS_v} + asS_s + aoS_{o+ai}S_i \tag{10}$$

$$R_{raster=avR_v} + asR_s + aoR_{o+ai}R_i \qquad (11)$$

where ET_{raster}, S_{raster}, R_{raster} are the total evapotranspiration, surface runoff, and groundwater recharge of a raster cell respectively, each having a vegetated, bare-soil, open-water and impervious area component denoted by *av, as, ao* and *ai* respectively.

Precipitation was taken as the starting point for the computation of the water balance of each of the components mentioned above of a raster cell, the rest of the processes (interception, runoff, evapotranspiration, and recharge) follow in an orderly manner. The description of each water balance with respect to land use format is described below.

Surface Runoff

Surface runoff was calculated in relation to precipitation amount in Equations 12 and 13, precipitation intensity, interception and soil infiltration capacity. Initially, the potential surface runoff (*Sv - pot*) was calculated as:

$$S_{v-pot=}C_{sv}(P-1) \qquad (12)$$

where, C_{sv} is a surface runoff coefficient for vegetated infiltration areas, and is a function of vegetation, soil type and slope. In the second step, actual surface runoff was calculated from the *Sv-pot* by considering the differences in precipitation intensities in relation to soil infiltration capacities.

$$S_{v=C_{Hor}S_v} - pot \qquad (13)$$

where CH_{or} is a coefficient for parameterizing that forms part of seasonal precipitation contributing to the Hortonian overland flow. The CH_{or} for groundwater discharge areas was equal to 1.0 since all intensities of precipitation contribute to surface runoff. Only high-intensity storms can generate surface runoff in infiltration areas.

Evapotranspiration

For the calculation of seasonal evapotranspiration, a reference value of transpiration was obtained from open-water evaporation and a vegetation coefficient as indicated in Equations 14 and 15:

$$T_{rv=cE_o} \qquad (14)$$

T_{rv} = the reference transpiration of a vegetated surface [LT^{-1}]; E_o = potential evaporation of open water [LT^{-1}] and c= vegetation coefficient [–]. This vegetation coefficient was calculated as the ratio of reference vegetation transpiration to the potential open-water evaporation, as given by the Penman equation as:

$$C = \frac{1 + {}^{\gamma}/_{\Delta}}{1 + {}^{\gamma}/_{\Delta}\,(1 + r_c/r_a)} \qquad (15)$$

γ = psychrometric constant [$ML^{-1}T^{-2}C^{-1}$]; Δ = slope of the first derivative of the saturated vapor pressure curve (slope of saturation vapor pressure at the prevailing air temperature) [$ML^{-1}T^{-2}C^{-1}$]; *rc* = canopy resistance [TL^{-1}] and *ra* = aerodynamic resistance [TL^{-1}].

Recharge

The last component, the groundwater recharge, was calculated as indicated in equation 15 as a residual term of the water balance, i.e.,

$$R_{v=}P - S_v - ET_v - E_s - I \qquad (16)$$

The spatially distributed recharge was therefore estimated from the vegetation type, soil type, slope, groundwater depth, and climatic variables of precipitation, potential evapotranspiration, temperature, and wind-speed. ET_v is the actual evapotranspiration [LT-1] given as the sum of transpiration T_v and *Es* (the evaporation from bare soil found in between the vegetation).

(ii) WetSpass Input Data

Groundwater recharge needs plenty of factors to put into considerations, especially land use/cover type, soil type, elevation and the hydro-meteorological parameters Appendix 1-5. The WetSpass model input parameters include the hydro-meteorological data, land use, soil elevation and slope data are for model calibration and simulation. The meteorological parameters required include rainfall, mean temperature, wind and potential evapotranspiration (PET). The inputs data represented in spatial distribution maps in ASCII format prepared by ArcGIS. The 32 stations with 30 years period used to show the spatial distributions of parameters were used in this study. The simulation was divided into two phases, namely, rainy season and dry season for all stations. The inputs of the model are described below.

Rainfall Data

Rainfall is a significant parameter that affects both the spatial and temporal availability of groundwater. Rainfall amount counts to be the primary variable in recharge amount of groundwater resources. In this study, climatic data from 1988-2018 for 31 stations were used as inputs data for WetSpass model. Historical spatial distribution showed in Appendix 1 and future inputs spatial distribution indicated in Appendix 2. Rainfall in the Lake Manyara catchment starts on November up to April and sometimes up to May. However, the northern part of the country characterized by a bimodal type of rainfall except in some areas in Manyara region experience the unimodal type of rainfall.

Seasonal rainfall is driven mainly by the migration of the Intertropical Convergence Zone (ITCZ) which migrates southwards in October to December, reaching the south of the country in January and February, and returning northwards in March, April and May. This causes the North and East of Tanzania to experience two distinct wet periods – the short rainy (or "*Vuli*") in October to December and the prolonged rainy (or "*Masika*") from March to May. The spatial distribution of the rainfall reveals that the highest amount of annual rainfall (greater than 700 mm) was reported in the northern (Ngorongoro and Karatu) and a small part in the southern part of the catchment (Appendix 1). The lowest amount of rainfall was reported in the eastern part of the catchment. This might be due to the high elevation in the north compared to other parts. The orographic effect seems to be more dominant in the areas.

Temperature

Temperature data used in this study as the input data obtained from reanalysis data that merged historical data and satellite data. Spatial temperature distribution indicates highest amount of temperature at the eastern part (around Monduli) and lowest in the northern parts (Ngorongoro and Karatu) as shown in Appendix 1. This might be due to high elevation location of Ngorongoro and Karatu.

Wind Speed

This used as the model input where by spatial distribution of the wind speed in the catchment as shown in (Appendix 1). The Southern parts during the rainy season experience high wind speed of about 3.3 m/s compared to the other parts, and the Northern part experience the lowest wind speed of 2.7 m/s and western part moderate wind speed. During the dry season, high wind speed experienced in the western parts of about 4.3 m/s compared to the other parts and lowest wind speed in the northern parts about 3.0 m/s.

Potential Evapotranspiration (PET)

Potential evapotranspiration (PET) defined as the amount of evaporation that would occur if a sufficient water source were available. In this study, DrinC software used to calculate PET which requires the availability of maximum temperature and minimum temperature for computation (Hargreaves & Samani, 1985). Calculated PET was in monthly results and later subdivided into two primary season's rainy season dry season. The Appendix 2 shows that the highest potential evapotranspiration in the rainy season was 158.5 mm, while in the winter was 138.6 mm, and was highest in the Western parts while in the dry season the average potential evapotranspiration 161.1 mm in the West part and lowest in the Northern parts with an average of 126.7 mm.

Groundwater Depth

Inputs of the spatial distribution of groundwater level of Lake Manyara catchment indicates high groundwater level in the Southern part and shallow groundwater level in the other part of the catchment. This groundwater level difference might be due to high elevation in the Northern parts compared to the Southern area. The figures were indicated in the Appendix 2.

Climatic Condition Projected

The spatial distribution of future climatic projections (Appendix 3) showed the inputs parameters used for WetSpass model. The same trend observed in most of the areas, although the only difference observed in the amount in the amount of spatial distribution. Rainfall, temperature and PET increased.

Elevation and Slope

The DEM map used in this study obtained from the ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) in which the imaging activities started since December 1999. The DEM product has a resolution of 30 x 30 meters. The downloaded map as the raster converted to ASCII format by ArcGIS ready for WetSpass input. Appendix 2 shows the elevation range from the lowest (minimum) elevation point in the catchment was 948 m around the lake and middle part while the highest was 3615 m in the Northern parts and Southeasterly parts of the catchment. The slope map of the catchment (Appendix 2) is derived from the digital elevation model (Dembélé & Zwart) using the 'slope' module in ArcGIS 10.5. The slope ranges from 00 to 47% with the highest slope in the north, east and south and at the edge of Western parts.

Land-use/ Land-cover

The Sentinel mission is the European Imaging Radar Observatory for the Copernicus joint initiative of the European Commission (EC) and the European Space Agency (ESA). Land use/cover maps used in this study was downloaded from the Sentinel 2A prototype Land cover with 20-Meter resolution (http://2016africalandcover20m.esrin.esa.int/download.php). The downloaded map of the respective shapefile (Appendix 4) of the catchment classified with the ArcGIS and later the WetSpass land use/cover classification adopted for the Lake Manyara catchment. After classification, the land use/cover converted from raster to ASCII format ready as the input data in WetSpass. In the catchment, the land use/land-cover type is largely dominated by grass (39.59%), whereas shrub covers almost 26.63%, agriculture (6.95%), mixed forest (6.65%), Lake and the rest (1.36%) is covered with the buildings, forest, wetland and bare land as shown in Table 3. In the WetSpass model, the land cover change for the rainy season and dry season were not considered because of the small difference among the land cover. Also, various studies showed the effects of land use/cover changes towards the groundwater recharge as the prerequisites (Narany *et al.*, 2017).

Table 4: Land-use type and area coverage in Lake Manyara catchment

Land-use type	Area (km^2)	Area (%)

Land-use type	Area (km^2)	Area (%)
Buildings	24.47	0.31
Agriculture	1490.34	18.82
Deciduous forest	4.99	0.06
Mixed forest	550.50	6.95
Shrub	2109.03	26.63
Bare land	62.77	0.79
Wetland	15.72	0.20
Lake	526.66	6.65
Grass	3135.55	39.59

Soil

The soil data used in this study is based on the soil texture classification developed by the United States Department of Agriculture (USDA) as shown in Appendix 5. Soil source obtained at https://data.isric.org/geonetwork/srv/eng/catalog. Data in Appendix 5 are characterized by clay, silt, sand and loam ranging from the fine textures (clay), through the intermediate textures (loam). Later the soil data adopted according to the WetSpass soil classifications. The input soil type from FAO indicates the catchment was dominated by 46% of silt, 19% of sandy loam, 13.86% loamy sand, 13.65% sand, 4%, sandy clay loam, 0.19% silt clay loam, 0.05% silt and 0.02% loam as indicated in Table 4. The area is dominated by silt soils, which have high water retention capacity and air circulation and not much conducive for recharge capability.

Table 5: Soil type and area coverage in the Lake Manyara catchment (FAO)

Soil type	Area (km^2)	Area (%)
Sand	1081.71	13.65
Loamy sand	1098	13.86
Sandy loam	1581.39	19.96
Silt loam	3696.03	46.64
Silt	4.14	0.05
Loam	1.71	0.02
Sandy clay loam	57.24	0.72
Silty clay loam	15.39	0.19
Water	388.8	4.91

The spatial distribution of future climatic projections (Appendix 3) showed the inputs parameters used for WetSpass model.

3.3.4 WetSpass Model Calibration and Validation

Model calibration and validation were performed by comparing the simulated and the calculated groundwater recharge using the water balance equation for the period of 2010 to 2015. The calibration process involved the repeatedly model run in adjusting model parameters within the calibration range to minimize the differences between model output and the calculated results. The model was then evaluated by assessing goodness of fit using the scatter plot and coefficient of determination (R^2) before applied the model for the 30 years (1988-2018) groundwater recharge estimation.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Spatial and Temporal Distribution of Rainfall and Temperature

4.1.1 Monthly Mean Rainfall and Temperature

The results for the mean monthly rainfall, maximum and minimum temperature for Babati, Monduli and Mbulu District office meteorological stations within the Lake Manyara catchment for the period 1988-2018 are presented in (Fig. 4). The results for rainfall (Fig. 9a, b and c) showed two rainy seasons between March and May (MAM season) and between October and December (OND season). Between June and September (JJAS) the dry condition exists over the catchment. The maximum temperature (Fig. 4 d, e and f) indicates the highest temperature occurred in October and the lowest temperature in June and July. These conditions might be caused by various factors, including topography and availability of moisture. The results for the minimum temperature (Fig. 4 g, h and i) show the highest temperature in December and the lowest temperature in July. The present study found that the average rainfall from 1988-2018 was 780 mm/y, and the maximum and minimum temperatures were 27.8 ℃ and 15.0 ℃, respectively.

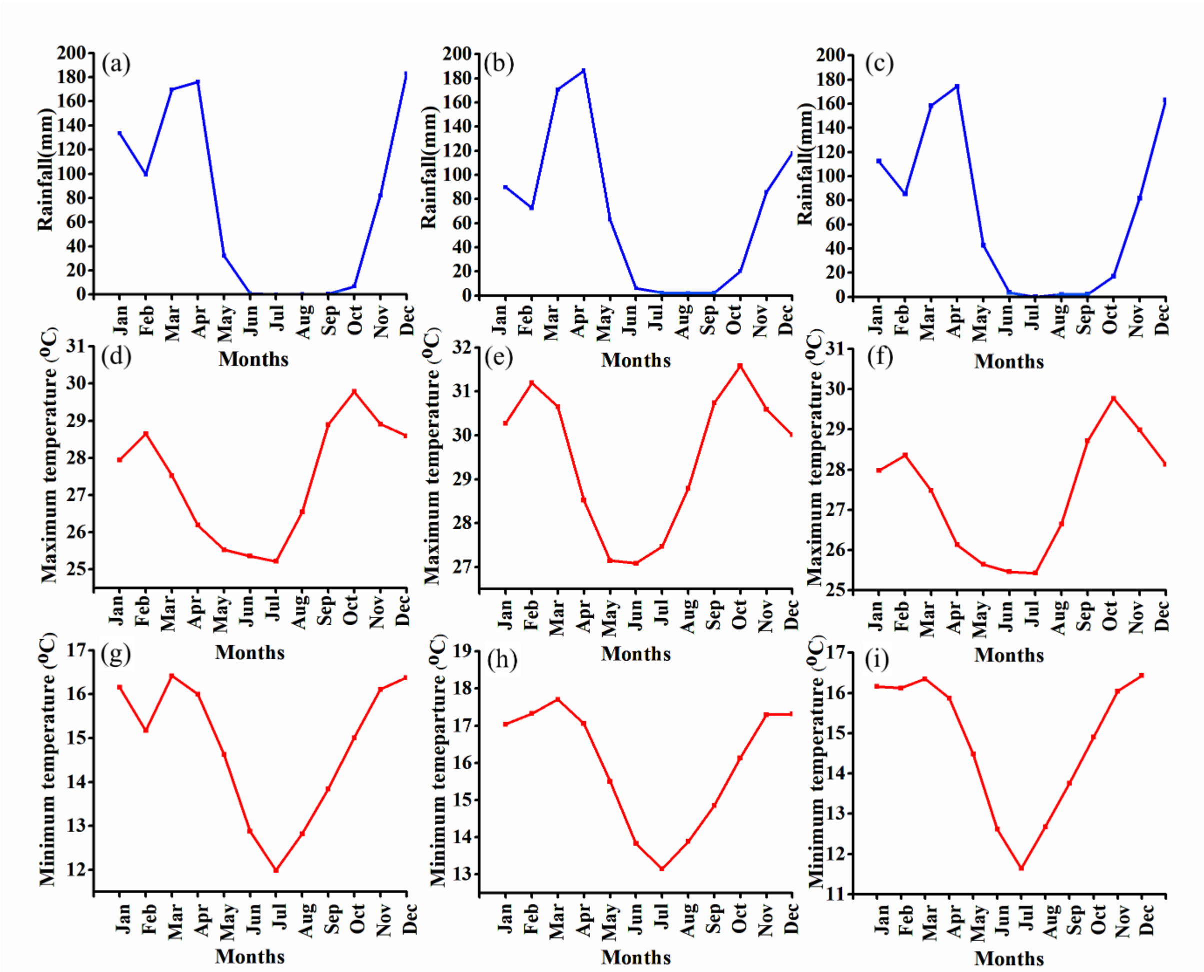

Figure 4: Mean monthly cycle of rainfall (a-c), maximum temperature (d-f) and minimum temperature (g-i) for Babati (a, d, g), Monduli (b, e, h), and Mbulu District office (c, f, i) from 1988-2018

4.1.2 Spatial-temporal Variability of Rainfall and Temperature

The results for the annual series plots of rainfall for the individual station (Fig. 5), Eastern, Western and the Southern part of the catchment (Fig. 6) show a year-to-year variability with a mean annual value of 780 mm between 1988 and 2018. The results of the annual mean of maximum temperature (Fig. 9a - d) and the annual mean of minimum temperature (Fig. 9e - i) indicate high variability within 30 y. The average of the annual minimum temperature showed an increasing trend at the rate of 0.025 ℃/y compared to the maximum temperature that showed a slight yearly decrease in trend in all stations. Climatic condition variability seems to be a common phenomenon to most of the tropical regions as observed by the study conducted by (Alemu *et al.*, 2019).

The spatial distribution of the annual rainfall reveals that the highest amount (> 700 mm) was received in the Northern part (Ngorongoro and Karatu) (Fig. 7), while the lowest rainfall amount of about <600 mm is noticed in the eastern part of the catchment. This observed difference in spatial rainfall might be due to the high elevation in the north where orographic effect seems to be more dominant compared to other regions. In case of temperature (Fig. 8), the spatial distribution revealed an annual average of both maximum and minimum temperature is high in the eastern part (around Monduli) and low in the northern regions (Ngorongoro and Karatu). This study reveals a strong spatial variation of temperature and rainfall (Fig. 7 and 8). This may be attributed to the high elevation of Ngorongoro and Karatu at the northern part of the catchment. This variability in climate has implication in various field including hydrology and agriculture due to over-dependence on rainfed agriculture and livestock keeping in the catchment.

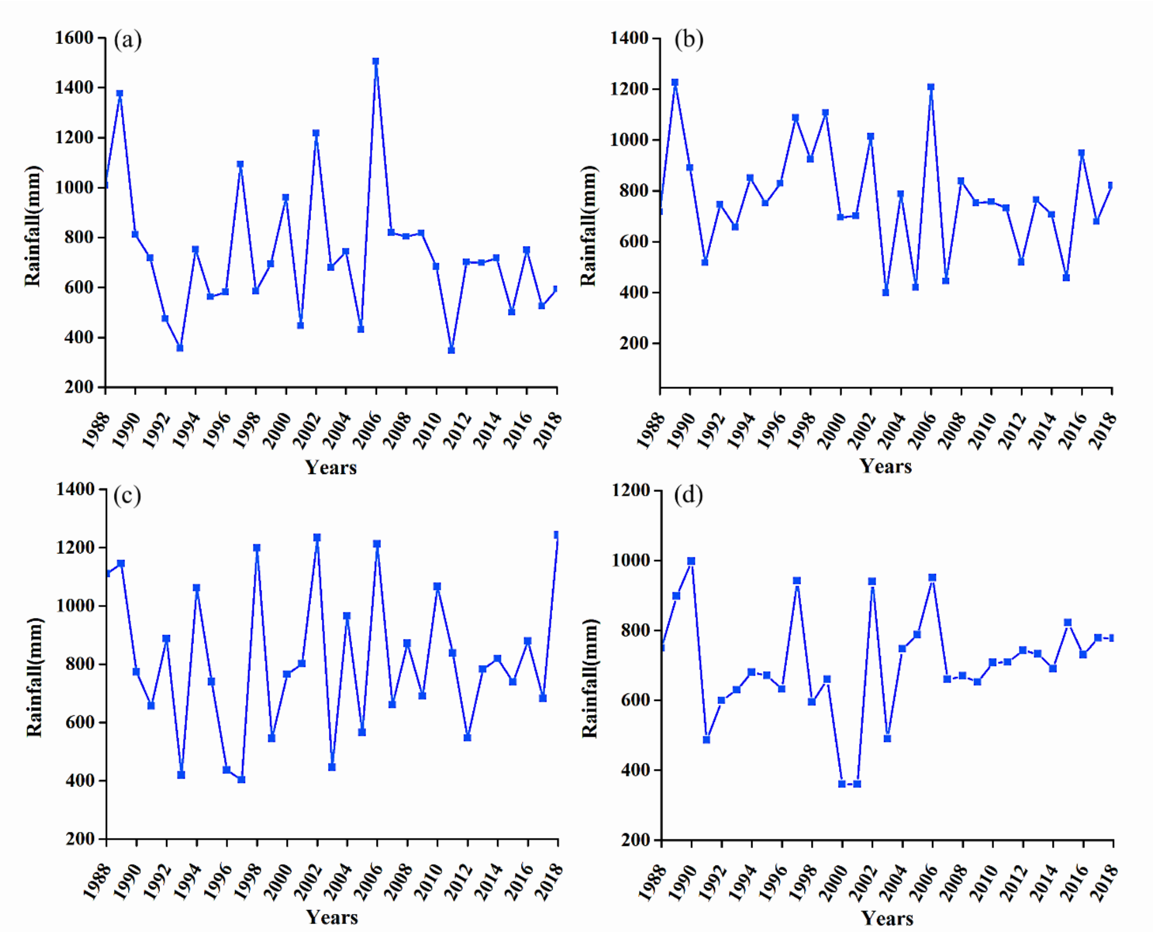

Figure 5: Annual rainfall for (a) Babati (b) Monduli (c) Mbulu District Office (d) Arithmetic mean of the catchment 1988-2018

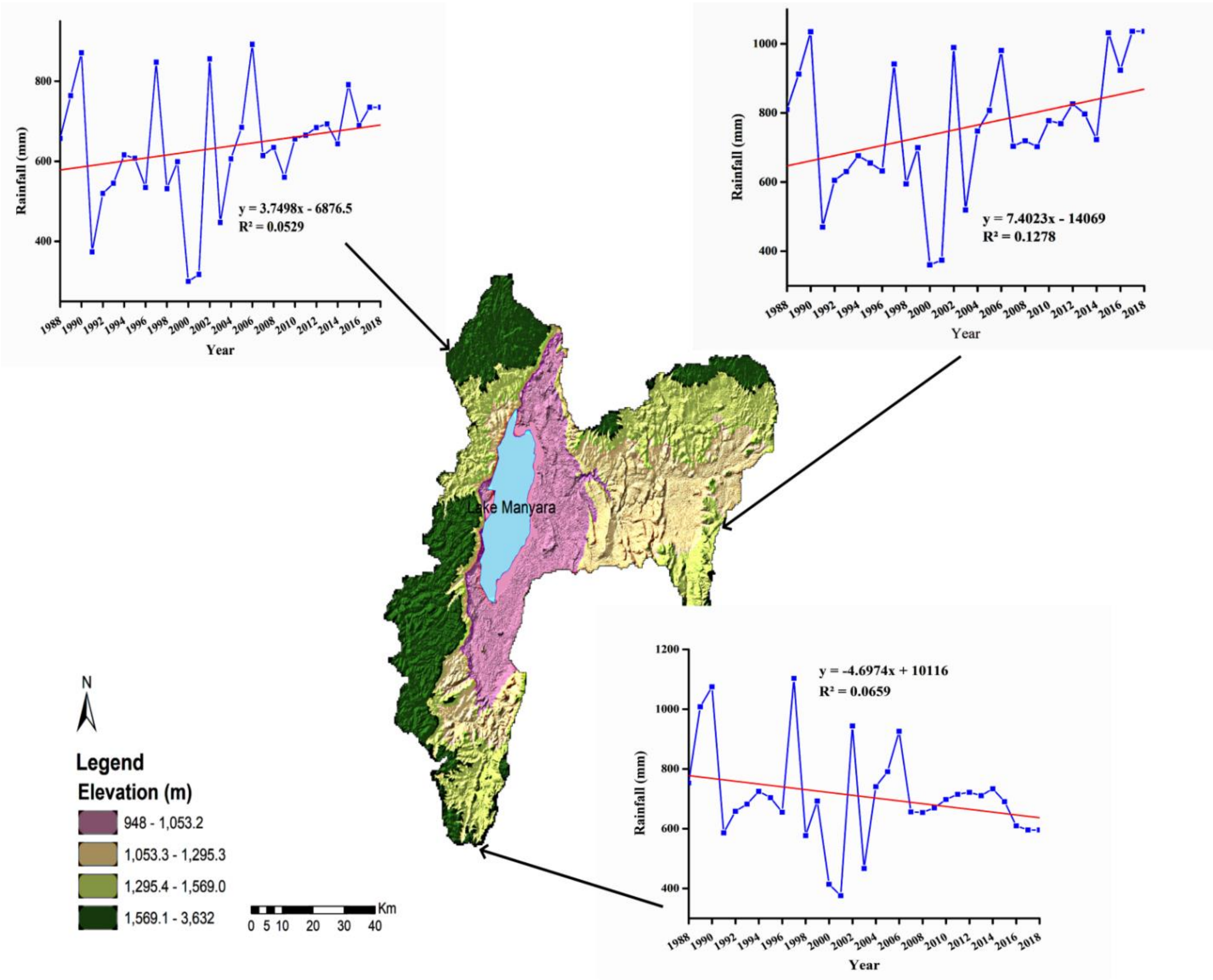

Figure 6: Annual rainfall patterns for the arithmetic mean of stations in east, south and west part of the Lake Manyara catchment from 1988-2018

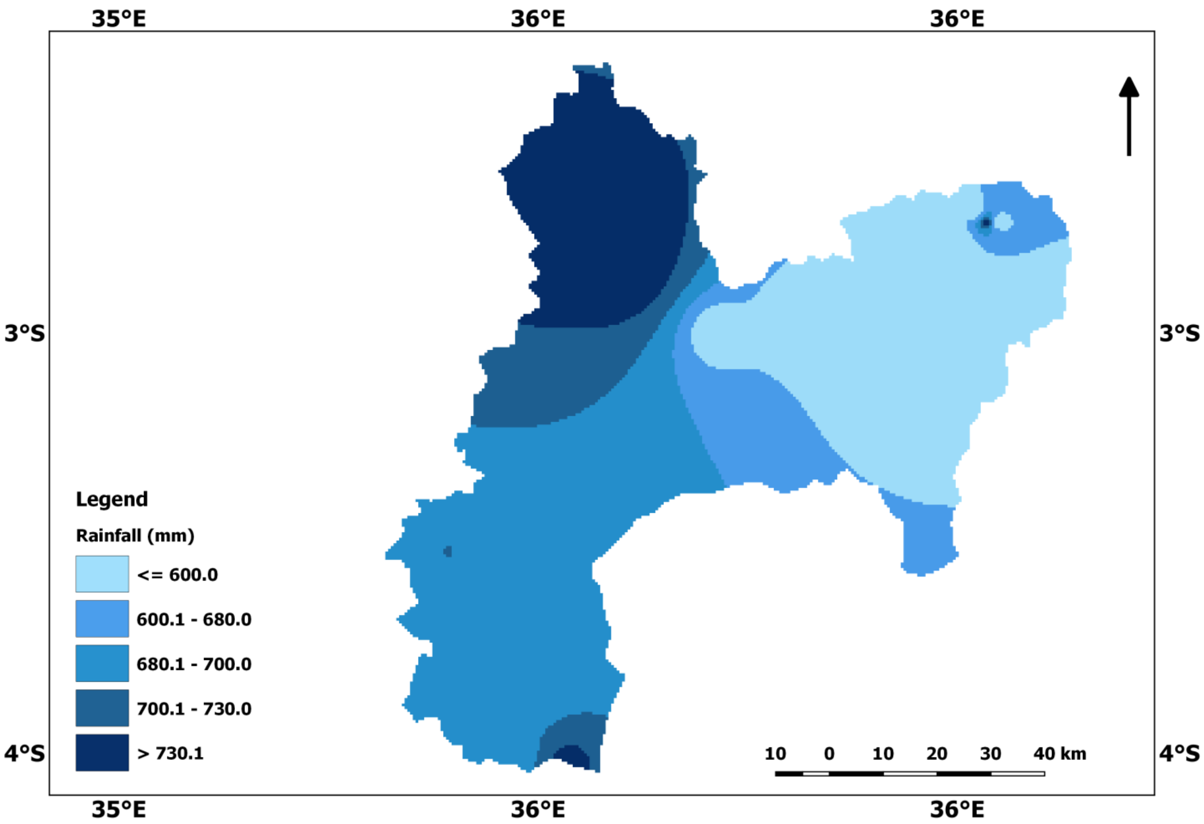

Figure 7: Spatial distribution of mean annual rainfall for the period 1988 to 2018 in Lake Manyara catchment

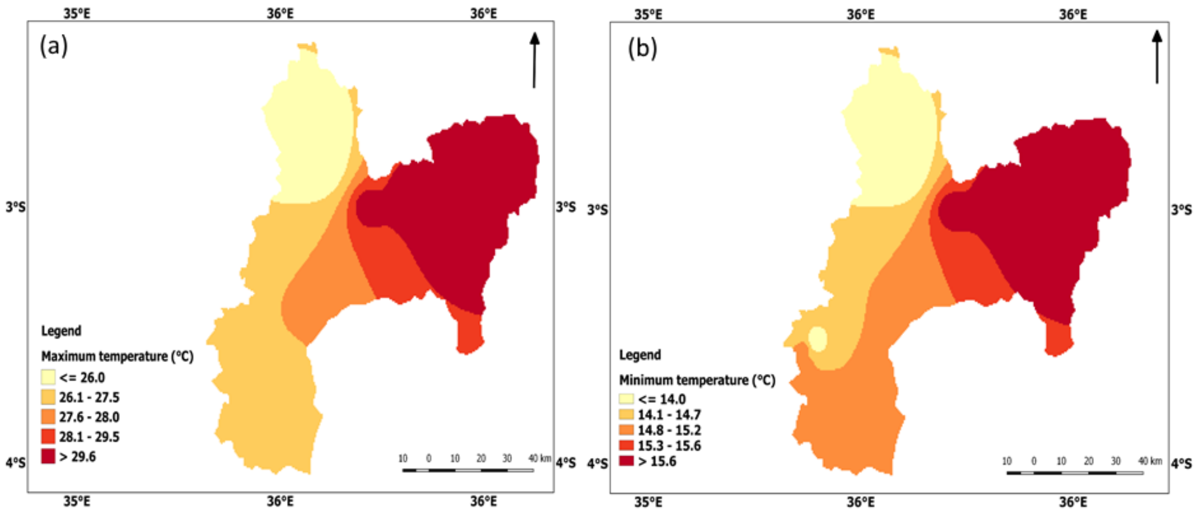

Figure 8: Spatial distribution of mean annual (a) Maximum temperature (b) Minimum temperature for the period 1988 to 2018

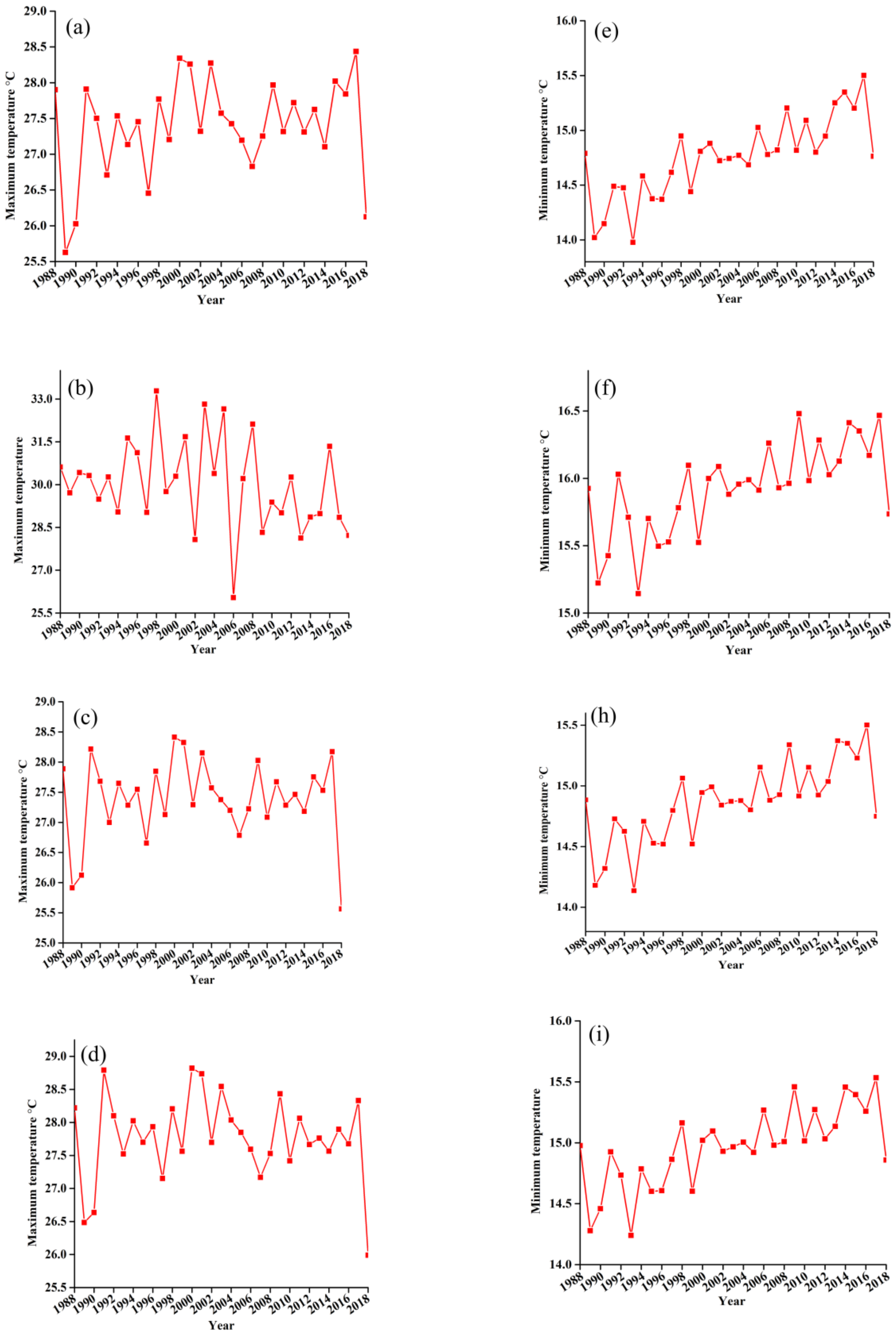

Figure 9: The annual maximum temperature for (a) Babati (b) Monduli (c) Mbulu District Office (d) Arithmetic mean of the catchment and annual maximum temperature of (e) Babati (f) Monduli (g) Mbulu District Office (h) Arithmetic mean of the minimum temperature of the catchment from 1988-2018

4.1.3 Mann–Kendall Trend Test of Annual Rainfall and Temperature

The results for the MK trend analysis Table 5a of rainfall indicate a non-significant decreasing trend of rainfall for the three stations and the entire catchment. A decreasing trend in the annual rainfall at the rate of 4.3 mm/y and 5.0 mm/y was noticed for the Babati and Monduli stations respectively, while an increasing trend is noticed for the Mbulu station. The entire catchment also showed a decreasing trend in annual rainfall at a rate of 5 mm/y. The MK test also computed for the maximum temperature reveals a non-significant increase trend in two out of the three stations (Table 5b). Unlike maximum temperature, the mean annual minimum temperature showed a significant positive trend for the three stations (Table 5c).

This means that during the night, temperature increase significantly due to the release of long wave radiation. The minimum temperature showed an increasing trend at the rate of 0.025 ℃/y compared to the maximum temperature that showed a slight yearly decrease in trend in all station and for the entire catchment in any reason. Similar studies in different parts of the world didn’t indicate significant statistic trends in annual rainfall (Mengistu *et al.*, 2014). Substantial variability of warming trends of mean annual minimum temperatures was reported significantly than maximum temperature by other studies that covered different periods and spatial scales (Tesso *et al.*, 2012; Chang’a *et al.*, 2017).

Table 6: List of Man Kendal and Sen's slope result for annual (a) Rainfall (b) Maximum temperature (c) Minimum temperature

Station	*Z*	Sen's slope	*S*	*Var (S)*	Kendall's *tau*	*P*-value	*α*	
Babati	-0.85	-4.32	-51	3461.67	-0.11	0.4	0.05	
Monduli	-0.85	-5.08	-51	3461.67	-0.11	0.4	0.05	(a)
Mbulu District office	-1.36	-11.97	-81	3461.66	-0.17	0.17	0.05	
Catchment	1.557	4	97	3801.67	0.2	0.12	0.05	
Station	*Z*	Sen's slope	*S*	*Var (S)*	Kendall's *tau*	*P*-value	*α*	
Babati	1.02	0.01	61	3439.67	0.13	0.31	0.05	
Monduli	-1.82	-0.05	-108	3441.33	-0.24	0.07	0.05	(b)
Mbulu District office	0.07	0.03	5	3443	0.01	0.9	0.05	
Catchment	-0.46	-0.006	-29	3779.67	-0.06	0.65	0.05	
Station	*Z*	Sen's slope	*S*	*Var (S)*	Kendall's *tau*	*P*-value	*α*	
Babati	4.82	0.03	281	3380.33	0.63	0	0.05	
Monduli	4.07	0.03	238	3394.67	0.53	0	0.05	(c)
Mbulu District office	4.39	0.03	259	3461.67	0.56	0	0.05	
Catchment	4.07	0.024	248	3682	0.53	0	0.05	

4.1.4 SPI Analysis of Rainfall

The analysis focused on understanding the sensitivity of SPI to rainfall deviation from the annual mean and discovered the wet, normal and dry condition in the area. The SPI analysis results (Table 6) shows the signal of normal conditions in all stations with few years showing evidence of wetter and drier conditions. From the SPI results, more positive values were obtained indicating a wet year in the catchment mostly in the year of 2002 and 2006, whereas the more negative values obtained in the year of 1993 and 2003. In addition, the SPI results revealed that in the catchment drought conditions sustained more compared to the wet condition. Several studies show the increase in the intensity of drought in the country. This has been demonstrated by the number of studies which show the increase in drought severity with higher water demand as a result of evapotranspiration (Vicente-Serrano *et al.*, 2011; Yu *et al.*, 2013). Standard precipitation index has the advantage of being multiscalar, which is crucial for drought analysis and monitoring.

Table 7: Classification of the Standardized Precipitation Index and the corresponding number of years from 1988-2018

SPI values	Condition	Babati	Monduli	Mbulu District office
2.00 and above	Extremely wet	1	0	0
1.50 to 1.99	Severely wet	2	2	0
1.00 to 1.49	Moderately wet	1	3	6
0.99 to - 0.99	Normal	20	20	19
-1.00 to -1.49	Moderate drought	3	2	2
-1.50 to -1.99	Severe drought	2	3	4
-2.0 and less	Extremely drought	1	1	0

4.1.5 Rainfall Onset, Cessation and Length of the Rainy Season

(i) Onset and Cessation

Rainfall in Lake Manyara catchment exhibit variability for both time and space. The start and end of rainfall seasons for the period from 1988 to 2018 were given in Table 7. The results show inconsistency and high variations in the start of the rainy season for the different locations. On average, the rainy season starts in November and end in April or May, although the catchment location seems to have both uni-modal and bimodal mode of rainfall. The results also show that rainy season mostly starts early in the areas with high altitude around Karatu and Mbulu Agriculture stations and later in the western part around Monduli. A similar pattern was followed during the cessation period.

Table 8: Onset and cessation patterns of rainfall for 30 years in Lake Manyara Catchment from 1988-2018

	Onset				Cessation			
Year	Karatu	Babati	Mbulu District office	Monduli	Karatu	Babati	Mbulu District office	Monduli
1989	25-Nov	02-Jan	07-Dec	26-Dec	11-May	07-May	14-May	23-May
1990	12-Nov	12-Nov	29-Nov	08-Dec	17-May	06-May	30-Apr	09-May
1991	15-Nov	11-Dec	09-Dec	19-Dec	11-May	01-May	29-Apr	15-Apr
1992	18-Nov	30-Jan	24-Nov	09-Apr	15-Apr	15-Apr	18-May	08-May
1993	01-Jan	20-Nov	19-Nov	10-Nov	20-May	15-Apr	15-Apr	17-Apr
1994	02-Nov	16-Nov	06-Jan	18-Dec	18-Apr	15-Apr	03-May	15-Apr
1995	30-Oct	07-Nov	30-Nov	23-Nov	15-Apr	24-May	03-Jun	26-May
1996	27-Nov	26-Dec	02-Feb	17-Feb	28-May	28-Apr	13-May	29-Apr
1997	16-Nov	17-Nov	05-Apr	17-Nov	27-Apr	27-Apr	25-Apr	05-Jun
1998	04-Dec	17-Nov	02-Jan	17-Nov	05-Jun	15-Apr	19-May	26-May
1999	29-Nov	01-Dec	04-Dec	17-Nov	15-Apr	15-Apr	17-Apr	05-Jun
2000	07-Nov	08-Feb	23-Nov	17-Nov	20-May	21-Apr	17-Apr	25-Apr
2001	18-Nov	21-Nov	21-Nov	21-Nov	15-Apr	19-Apr	15-Apr	03-May
2002	28-Oct	06-Nov	21-Nov	22-Oct	15-Apr	15-Apr	25-Apr	01-May
2003	29-Oct	06-Nov	06-Nov	23-Oct	15-Apr	21-Apr	15-Apr	15-Apr
2004	23-Nov	09-Dec	05-Jan	03-Feb	15-Apr	15-Apr	01-May	02-May
2005	18-Dec	21-Nov	26-Nov	25-Dec	30-Apr	21-Apr	22-Apr	02-May
2006	23-Nov	28-Nov	02-Dec	16-Oct	03-May	15-Apr	22-May	19-May
2007	12-Oct	06-Nov	01-Nov	21-Oct	06-May	18-Apr	15-Apr	15-Apr
2008	01-Jan	19-Nov	16-Jan	22-Mar	16-Apr	07-May	03-May	08-May
2009	12-Nov	29-Nov	08-Nov	06-Dec	09-May	29-Apr	26-Apr	24-Apr
2010	08-Nov	07-Nov	22-Nov	10-Dec	17-Apr	15-Apr	03-May	12-May
2011	24-Nov	07-Dec	14-Nov	14-Feb	22-Apr	15-Apr	24-Apr	21-Apr
2012	02-Nov	09-Nov	14-Nov	24-Nov	15-Apr	15-Apr	18-Apr	18-May
2013	06-Dec	13-Dec	11-Dec	12-Nov	15-Apr	15-Apr	26-Apr	27-Apr
2014	28-Nov	21-Jan	05-Feb	03-Nov	13-May	15-Apr	29-Apr	01-May
2015	03-Nov	18-Nov	15-Nov	03-Nov	15-Apr	20-May	15-Apr	15-Apr
2016	15-Nov	09-Jan	08-Jan	17-Nov	25-May	15-Apr	11-Apr	09-May
2017	04-Nov	12-Nov	18-Nov	19-Nov	21-May	15-Apr	15-Apr	16-Apr
2018	18-Oct	05-Jan	22-Dec	01-Jan	15-Apr	09-May	15-Apr	15-Apr

(ii) Length of the Rainy Season

The results of the length of seasonal rainfall (LRS) in days were presented in Fig. 10 and show high variations and a decreasing trend except for the Mbulu District office station.

These variations may be attributed to variability in the onset and cessation of the season. The Mbulu region shows the lowest LRS compared to other regions, whereas Karatu indicates the highest LRS in the catchment. This variability in the duration of the rainy season suggests a possibility of the influence of climate change in these areas that may have implications on crop growth especially for crops, which require long seasons of rain to mature. Some study showed the contrast of the results of length of rainfall in different area. According to study by Kimambo and Ndeto (2018) there is little significant length of rainy season variations in Tanzania as observed of about 20%.

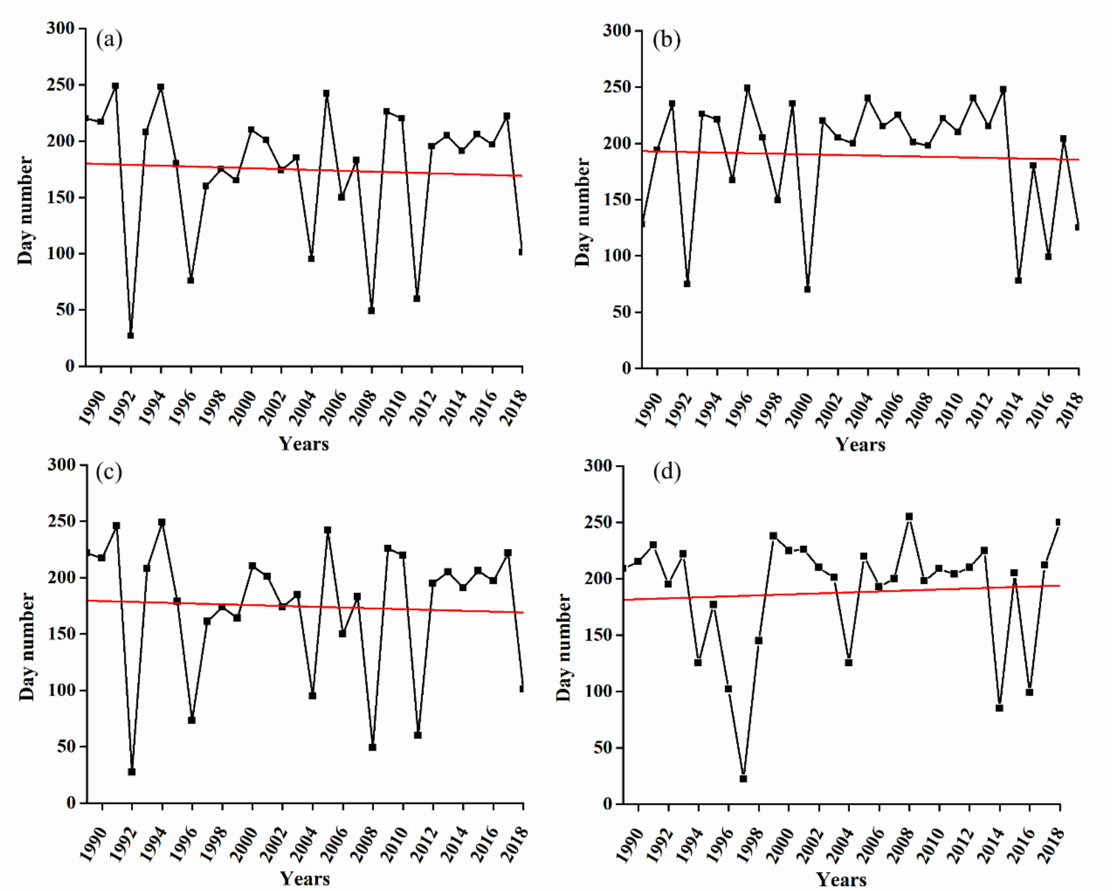

Figure 10: Length of seasonal rainfall in days (a) Karatu Agric (b) Babati (c) Monduli (d) Mbulu district

4.2 Future Climate Projections

4.2.1 Observed and Projected Monthly Average Rainfall and Trend 2021-2050

The results were grouped into two areas monthly average and annual average basis of the future scenario emission under RCP 4.5 and RCP 8.5. The study used the RCP 4.5 due to the area of the study in which some climatic measus to combat climate change have been considerd. Rainfall projection (Fig. 11) in the area indicates the shifting of the rainfall seasons and the significant increase in the annual rainfall trends. These changes in the shifting of the seasons and increase in trends may lead to changes in the daily or total decadal rainfall, probably due to the difference in rainfall intensity (Boko & Report, 2007). The projected rainfall seasons showed that the catchment rainfall season would start earlier than usual with the rainy season beginning in October, and ending in January, followed by a dry season in February, March, June and May. The second season starts in July and ends in September.

In the annual trends of the individual meteorological station and the arithmetic mean of the catchment (Fig. 12) shows the slight increase in rainfall amount. However, in the Lake Manyara catchment, the rainfall projection shows an increase in the annual rainfall trends by 2.1 - 5.0 mm for the period 2021-2050. The amount of the projected increased in monthly rainfall during the season this may cause more surface runoff in the area. Several studies indicate similar results of the projection around the country using the CORDEX climate downscaling data in which increase and decrease of rainfall results obtained (Chang *et al.*, 2001; Luhunga, 2017; Luhunga *et al.*, 2018).

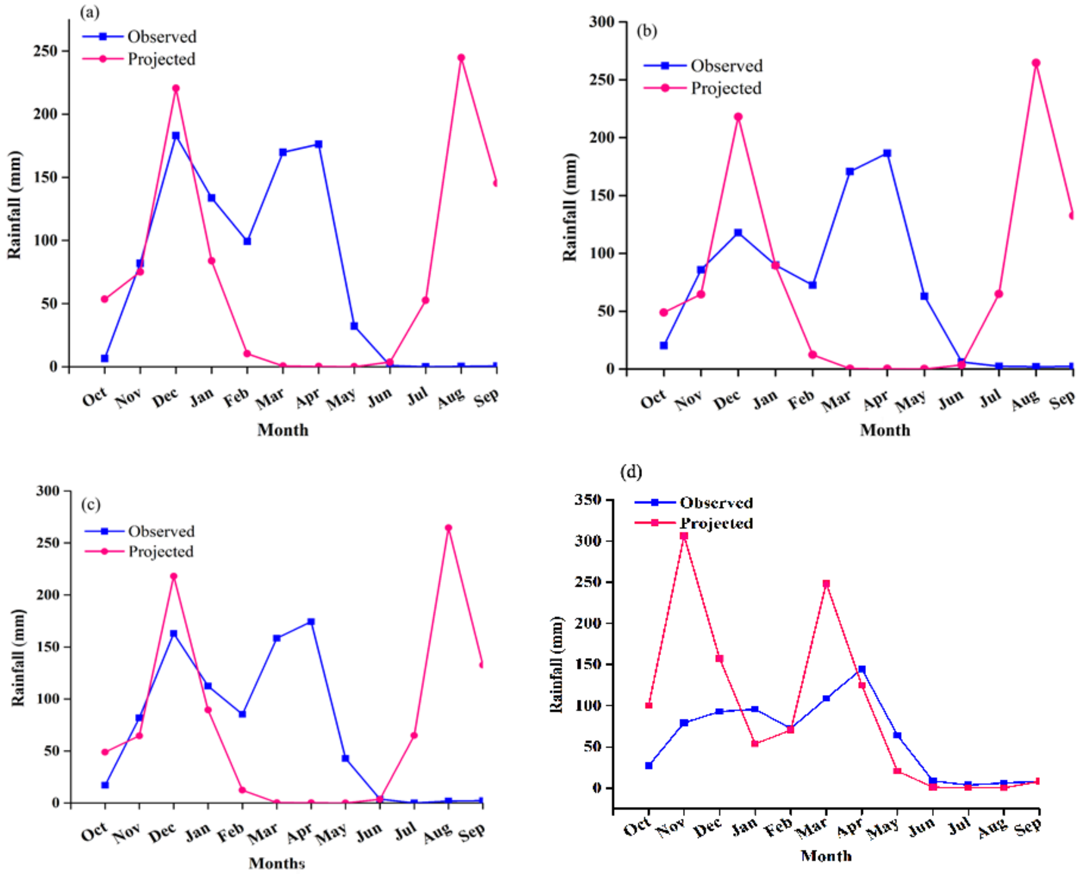

Figure 11: Projected and observed of monthly rainfall at (a) Babati (b) Monduli (c) Mbulu District (d) Karatu Agric from 2021-2050, and (d) Arithmetic mean of the whole catchment

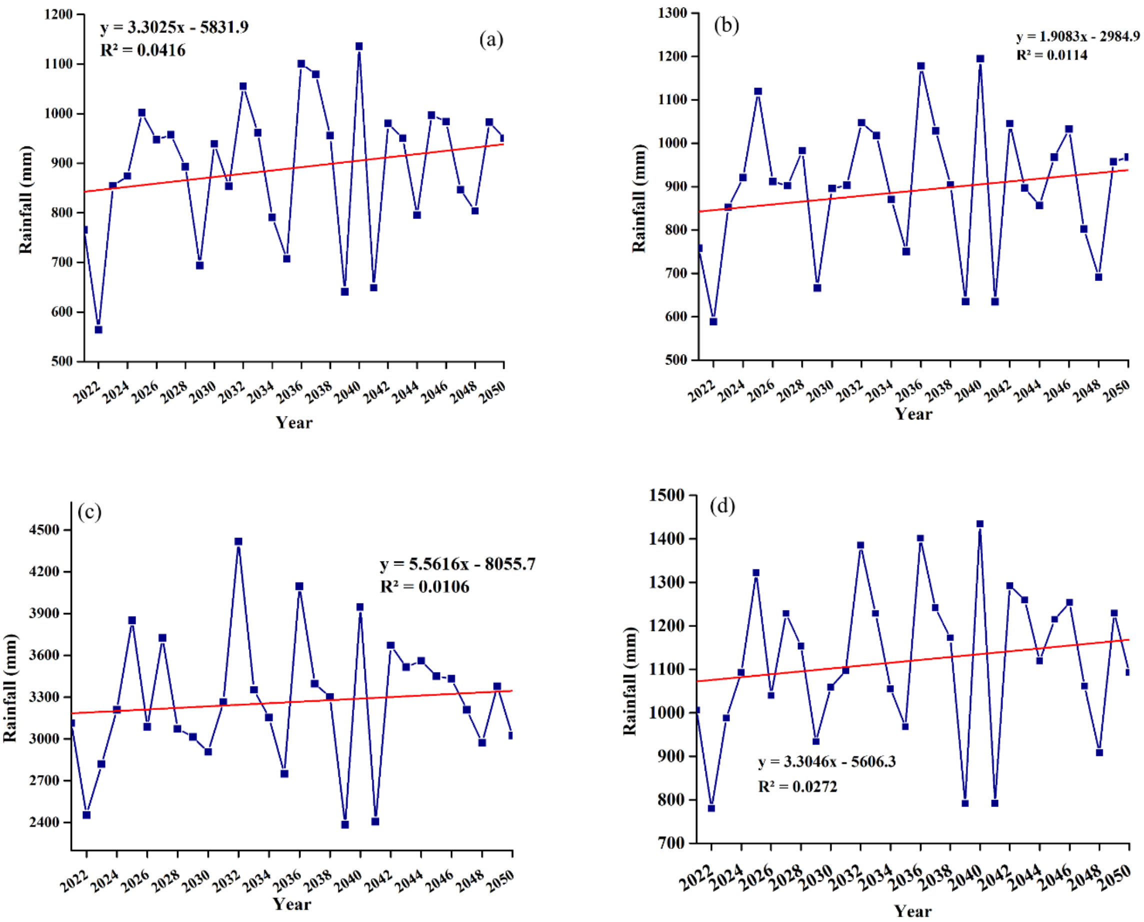

Figure 12: Projected annual rainfall trend at (a) Babati (b) Monduli (c) Mbulu District office (d) Arithmetic mean of the whole catchment from 2021-2050

4.2.2 Projected Temperature Monthly and Trend 2021-2050

From the results projection of the catchment, temperature showed that the monthly average (Fig. 13) the highest temperature values would be in February, September and October. The lowest temperature will be in November and December. The annual trend (Fig. 14) showed the increase in trend by the annual increment of 0.004 ℃ for almost the whole catchment. The spatial and temporal temperature will rise with significant level (R^2= 0.5) (Tumbo *et al.*, 2016).

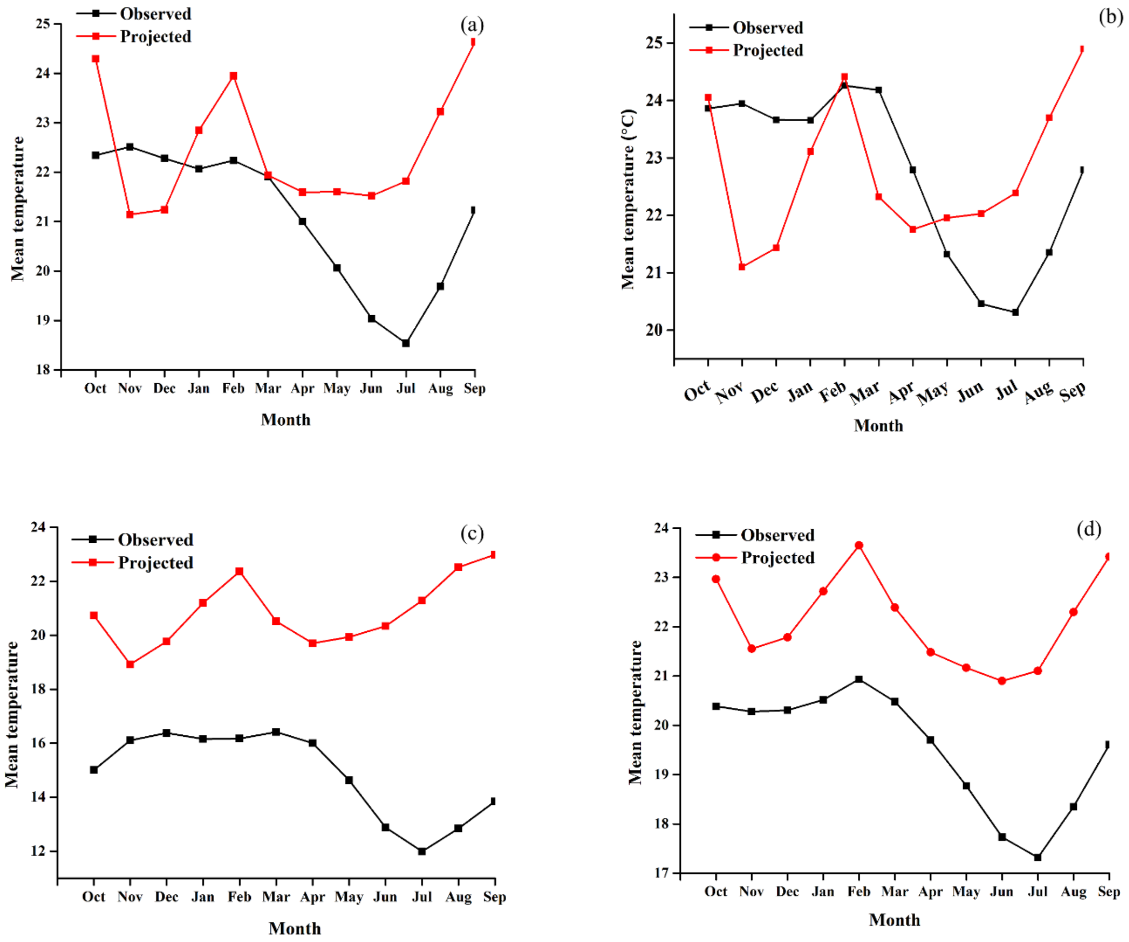

Figure 13: Projected and observed mean temperature at (a) Babati (b) Monduli (c) Mbulu District office (d) Arithmetic mean of the whole catchment

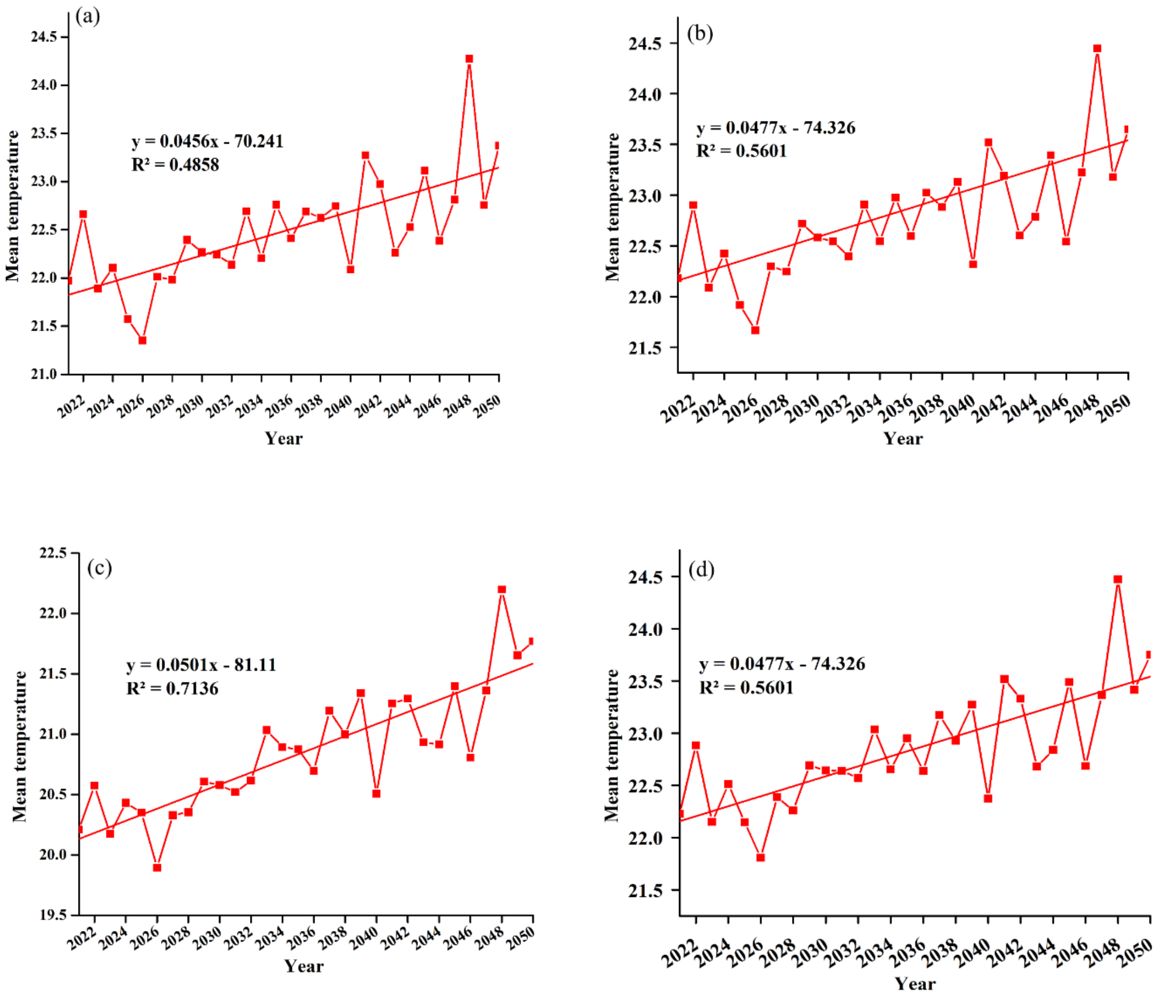

Figure 14: Projected annual trend mean temperature at (a) Babati (b) Monduli (c) Mbulu District office (d) Arithmetic mean of the whole catchment from 2021-2050

4.2.3 Projected Potential Evapotranspiration (PET)

Potential evapotranspiration was obtained after computation using projected temperature by using the Hargreaves Equation (17) (Allen *et al.*, 1998). Potential Evapotranspiration needed as the inputs for WetSpass model to obtain future recharge of the catchment.

$$PET = 0.0023(Tmean + 17.8)(Tmax - Tmin)0.5Ra \tag{17}$$

where PET is the potential evapotranspiration mm/day; $Tmax$ and $Tmin$ are average maximum temperature and minimum temperature in ℃ respectively; Ra extraterrestrial radiation (mm/day). The downscaled daily data for all the stations were used as an input for the WetSpass model for simulation of the hydrological water balance components responsible for the watershed.

4.3 Water Balance Estimation Outputs from WetSpass

The WetSpass model simulation results for the dry and rainy season time setup provides different water balance components including, runoffs, evapotranspiration, interception and recharge for the Lake Manyara catchment. The similar output obtained from various studies (Meresa & Taye, 2019) provides a better understanding of the hydrology and water balance at a catchment level in different parts of the world including Tanzania. These results are essential for policy and water resources management plans.

4.3.1 Surface Runoff

The model results for historical and future projections showed that the northern and southern parts in the catchment experience the highest amount of surface runoff for all season as compared to the other parts of the catchment. However, the eastern part indicates the lowest amount of surface runoff compared to other parts as (Fig.15) depicts. This difference might result from an increase in temperature amount in the catchment in the western parts. Generally, the significant parts of the catchment will experience the increase in the annual amount of surface runoff. The annual amount of surface runoff for the near future, estimated to be 429 mm/ y that provides 203 MCM per year after the summation of surface runoff of rainy season and dry season. The projected runoff of the Lake Manyara catchment estimated to 709 mm/y that will produce 519 MCM similarly, as found in previous studies (Meresa & Taye, 2019). Projection estimation of runoff component shows that the increase of surface runoff parallels to the rise in rainfall projected in the catchment.

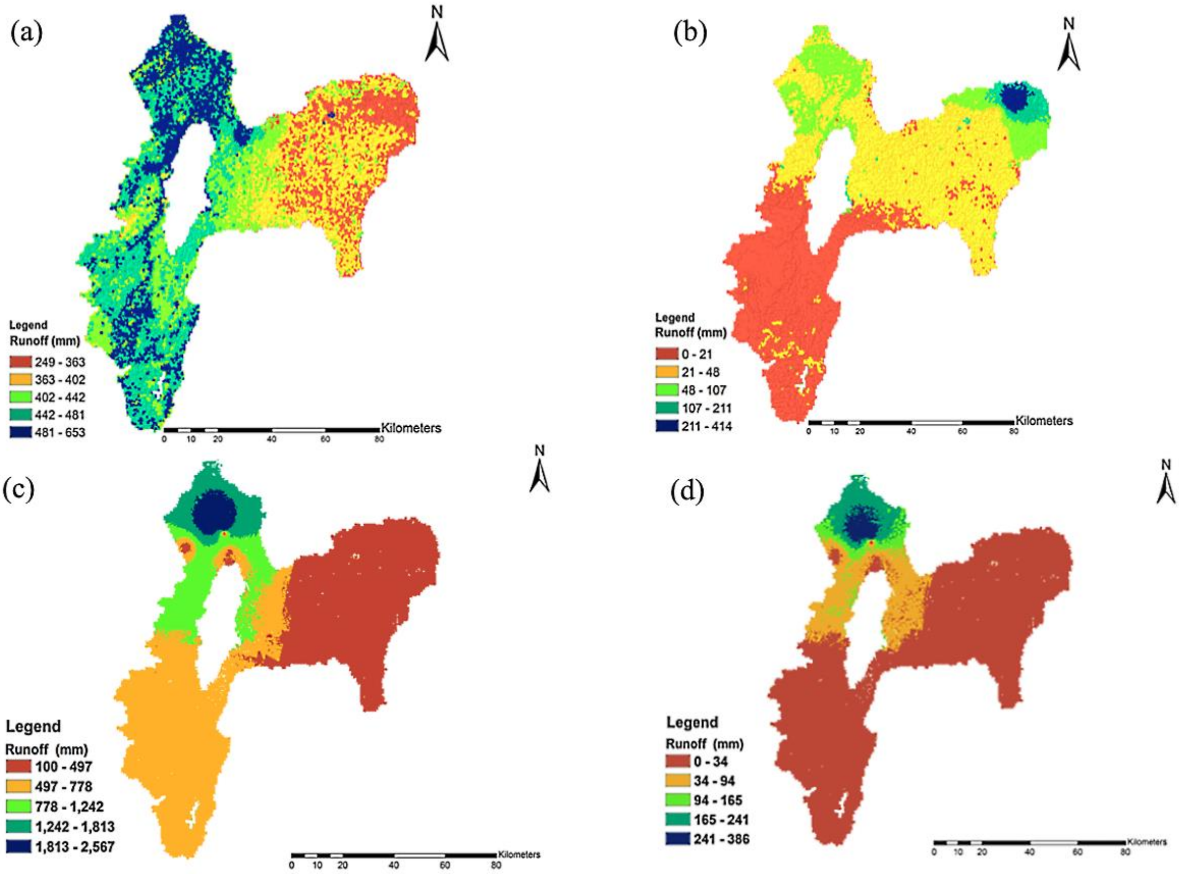

Figure 15: (a) Current rainy season runoff (b) dry season runoff (c) projected rainy season runoff (d) projected dry season runoff

4.3.2 Evapotranspiration

The results for the Actual Evapotranspiration (AE) as estimated by WetSpass model (Fig. 16) showed the large area in the western part has a high amount of AE compared to other parts while in the very small part in the catchment experience low AE. The results estimated 2.9 mm/y of transpiration from 1988-2018 that produce 2.1 MCM per year. In addition, the results showed that the future evapotranspiration estimated to be 199 mm/y that will provide potentiality of 1.5 MCM of the amount of water per year.

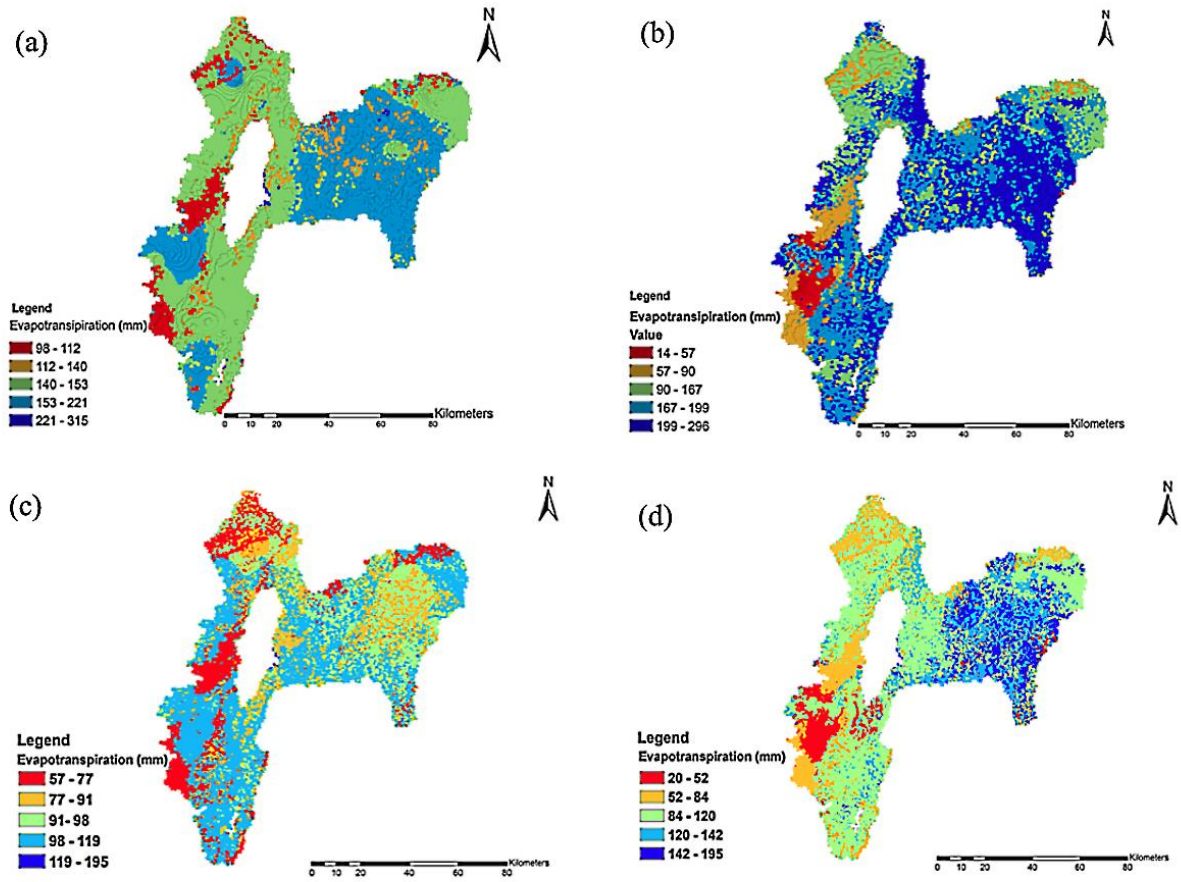

Figure 16: Evapotranspiration in Current rainy season (b) evapotranspiration in dry season (c) evapotranspiration in projected rainy season (d) evapotranspiration in the projected dry season

4.3.3 Recharge

The results from the WetSpass simulation of long-term biophysical and hydro-meteorological showed the seasonality differences in recharge amount (Fig. 17). The recharge amount can have a minimum average of zero or negative, especially in the dry season. This was due to high evapotranspiration during the dry season. Therefore, the historical average annual groundwater recharge from the amount of water infiltrated in the aquifer give the total recharge of 53 mm/y with the groundwater potentiality of 1.5 MCM per year. In the future groundwater recharge estimation expected to be 88.5 mm/y with the groundwater potentiality of 4.2 MCM in the Lake Manyara catchment. The estimated projected recharge amount of the Lake Manyara catchment indicates the increase of recharge despite the rise of temperature to evaporate the water. This might be due to the projected increase of rainfall in the catchment. Therefore, the amount of rainfall will be higher than the amount in temperature. The WetSpass results in Table 8 show the seasonality and annual amount of water balance in the catchment.

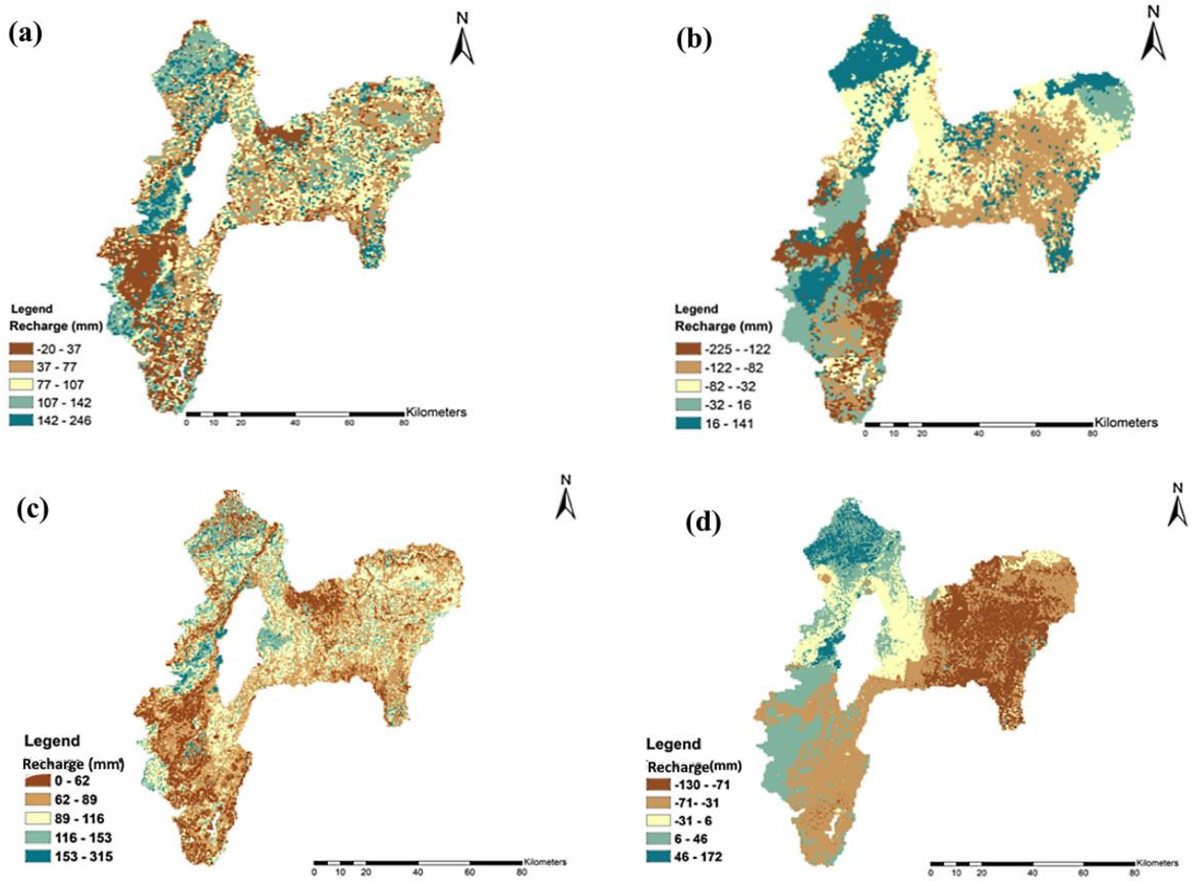

Figure 17: Current rainy season recharge (b) dry season recharge (c) projected rainy season recharge (d) projected dry season recharge

Table 9: Water balance components for historical 1988-2018 and projected 2021-2050 of the Lake Manyara catchment

	Water balance component	Rainy season	Dry season	Annual
Historical (1989-2018)	Evapotranspiration	1023769732	1115732342	2139502073
	Runoff	2933991827	203463063.2	3137454891
	Recharge	596896158.3	-447695012.7	149201145.6
Projected (2021-2050)	Evapotranspiration	700677085.5	835635264.3	1536312350
	Runoff	4925434901	260605828.1	5186040729
	Recharge	643869180.7	-222361275.1	421507905.6

4.4 Groundwater Potential Recharge Zones

According to the simulated averaged hydro-meteorological parameters from 1988-2018, the results indicated that the three zones of potential recharge in the catchment include low, medium and high recharge zones as indicated (Fig. 18). The results of the potential groundwater recharge zones in Lake Manyara catchment include the Northern part (around Ngorongoro), Western and Southwestern (Buger ward and Mbulu). These zones showed high recharge potentiality within the catchment however, the potentials varried from area to area. This variation was due to various factors including land cover and soil textures; for example, the area with plenty of sandy soil showed high rechargeability compared to other texture classes of the soil.

The total potential recharge area for the whole Lake Manyara catchment was about 23% of the whole catchment. Understanding potential groundwater recharge zones in Lake Manyara catchment is essential for the policy formulation and groundwater resource management plans; mainly, for the communities in the Lake Manyara catchment which depends on groundwater for 80% of their daily activities.

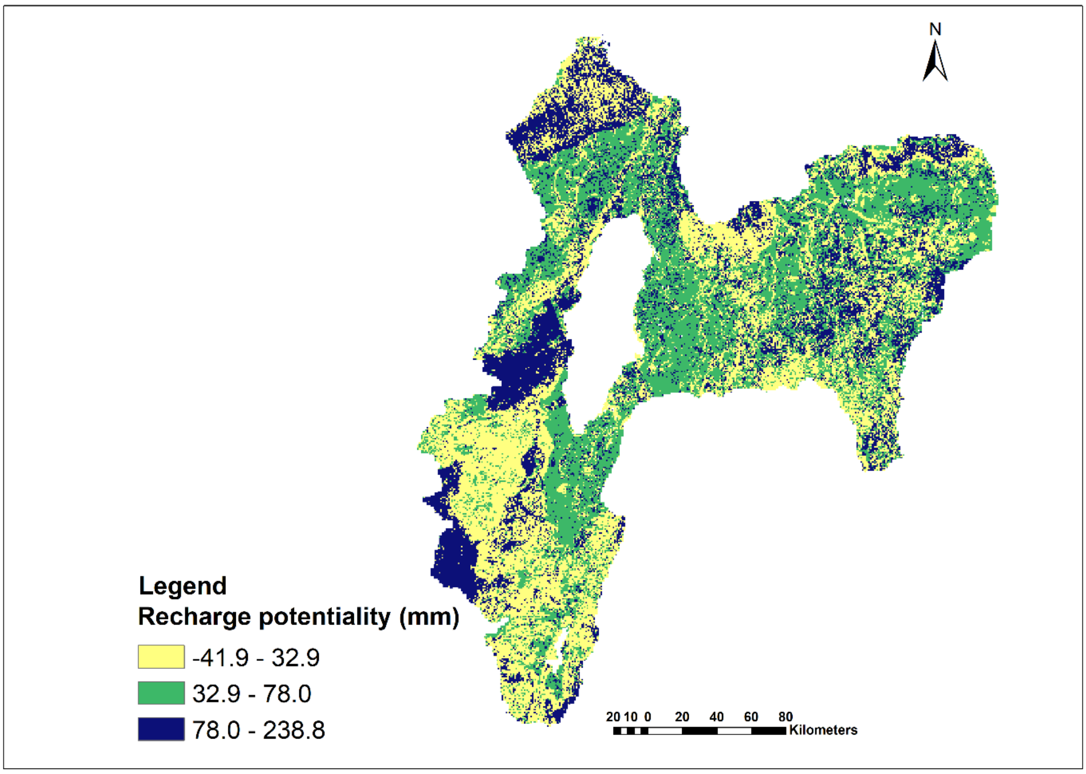

Figure 18: Groundwater potential recharge zones

4.5 Discussion

From this study, climate status of Lake Manyara catchment showed high variability in both spatial and temporal rainfall and temperature in the entire catchment. This climate variability has significant impacts on hydrology and water resource availability. The results revealed a decreasing trend in rainfall in historical data, while the maximum and minimum temperature indicates increasing trends in the area. Drought condition shows the signal at large compared to wet condition while dry spell shows an increase in frequency in the area. The start and end of the rainy season were inconsistent in most of the stations leading to high variability in the length of the rainy season. The future climatic projection result indicates the catchment will experience an increase of both rainfall and temperature; and at the same time the shifting of the seasonal rainfall in the area.

The final outputs of the WetSpass model obtained in the rainy season and dry season time steps for historical and future scenarios. Estimation results showed a reasonable agreement between measured and simulated recharge estimation. The model performance over the 10 years' verification period results shows the R^2 = 0.9 and *RMSE* = 4.86. Furthermore, the results for groundwater potential zones indicate a relatively small region of about 23% of the whole catchment has recharge potential. The historical and future estimated annual groundwater recharge was 53.9 mm/y and 88.5 mm/y with the potential recharge of 149 MCM per year and 421 MCM respectively under the same land use/land cover type of the catchment. These amounts showed that from the annual rainfall, only 6.7% contributed to recharge of the aquifer and 8.1% will be expected to contribute to the near future.

The historical mean average surface runoff estimation was 429 mm/y that contribute to 203 MCM compared with the future mean annual surface runoff will be 709 mm/y that will contribute to 519 MCM of surface runoff. In evapotranspiration, the historical mean annual estimation was 295 mm/y, which contribute to 213 MCM while in the future evapotranspiration will be 199 mm/y that will provide potentiality of 1 536 MCM of the amount of water per year. However, the most potential recharge zones in the catchment identified around the northern part (around Ngorongoro), western and south-western (Buger ward and Mbulu).

The results from this study are reliable for other studies, policy formulations, water resources management plans and climate change with adaptation measures. This result serves as a valuable input to pre-informed planning of water resources within the studied catchment and across the country. Therefore, climate change policies in the basin should include adaptation measures such as changing of crop type and improving water productivity and irrigation at the farm and basin scales. In particular, policy-makers should emphasize on the approach in minimizing agricultural water use through changing crop patterns as an effective solution for the basin’s water problems.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

Scientific evidence from this study was aligned with local perceptions that climate change in terms of rainfall decrease has implications on the trend of water resources specifically groundwater. The trend of the recharge rate corresponds to the trend of rainfall that shows a slight declining pattern in the last 30 years compared to other reports by Tanzania mistry of water. This has direct impact on crop farmers and wild animals located within the Lake Manyara catchment. In maintaining availability of groundwater resource, reliable rainfall for recharge required to available. However, other factors also supposed to be in consideration like soil type, land use/ land cover, slope and elevation.

The results showed that, the status of Lake Manyara catchment showed high variability of both temporal and spatial climate variability. The results revealed a decreasing trend in rainfall in historical data, while the maximum and minimum temperature indicates increasing trends in the area. The future climatic projection result indicates the catchment will experience an increase of both rainfall and temperature; and at the same time the shifting of the seasonal rainfall in the area. The historical and future estimated annual groundwater recharge was 53.9 mm/y and 88.5 mm/y with the potential recharge of 149 MCM per year and 421 MCM respectively under the same land use/land cover type of the catchment. These amounts showed that from the annual rainfall, only 6.7% contributed to recharge of the aquifer and 8.1% will be expected to contribute to the near future.

5.2 Recommendations

Generally, the future likely changes in rainfall and temperature is positive and will increase in the period from 2021 to 2050. Hence, people have to be aware and take actions as per necessary. The water resources are potentially available in Lake Manyara catchment is useful for irrigation use, livestock consumption and potable water for the resident people. Wise use of these water resources potential has paramount importance. Hence, increased exploitation together with climate change stresses towards these water resources is much more pronounced. Regardless of the increment of the water recharge in the catchment, wisely use of the water resources is much more encouraged.

Knowing the annual and seasonal simulated long term average annual groundwater recharge and water balance components is useful in such a way that:

(i) Future studies will require considering groundwater recharge with respect to land use/land cover and population changes in the catchment.

(ii) Groundwater studies should be conducted to generate more information for aquifers and input data for groundwater models.

(iii) This study also recommends easier accessibility to available information, e.g. meteorological data, hydrological data, land use and soil in the Lake Manyara from respective data custodian authorities.

(iv) Further studies could also be conducted to establish artificial recharge mechanism and water harvesting systems in the catchment as indicated by the WetSpass model results from this study.

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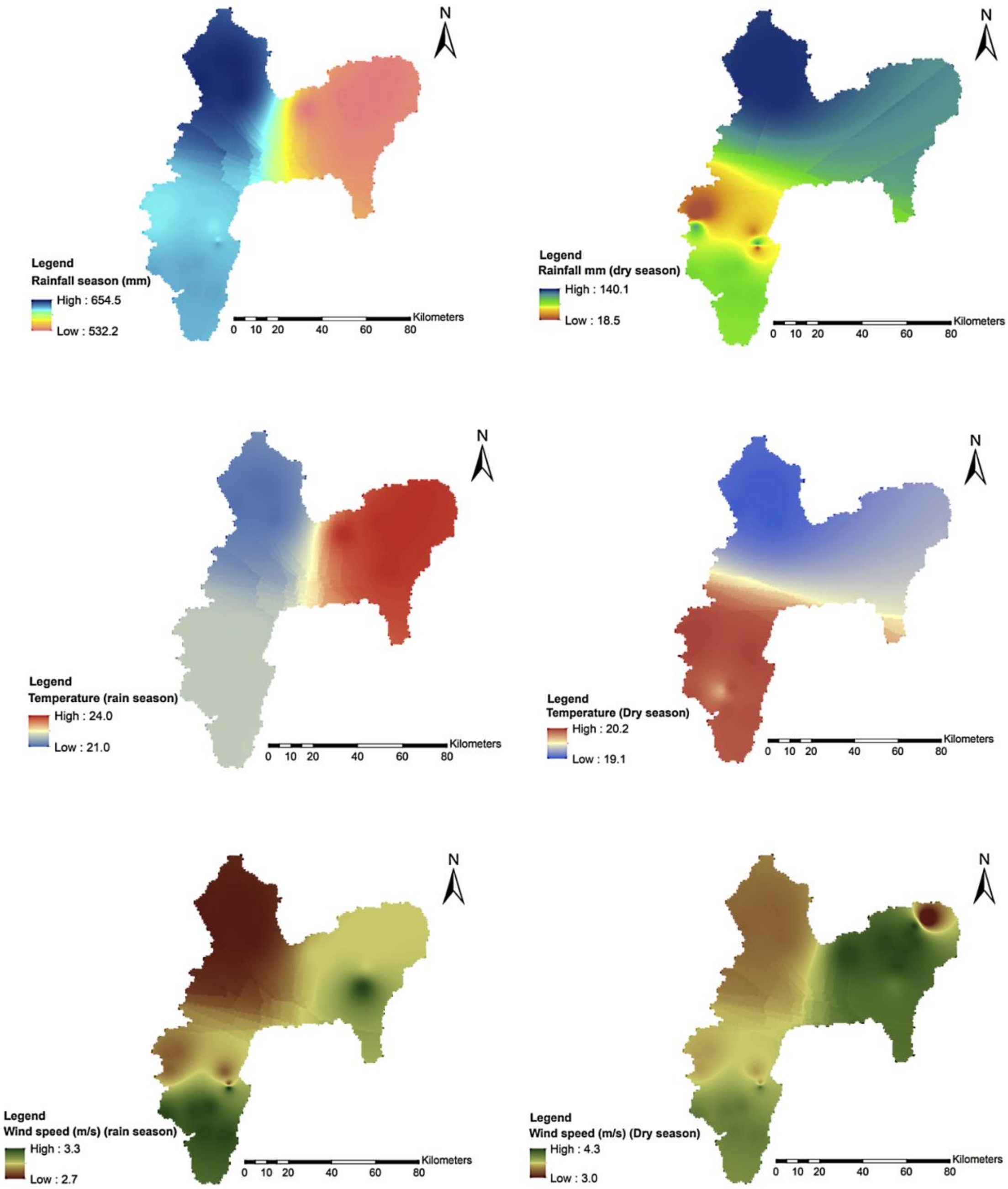
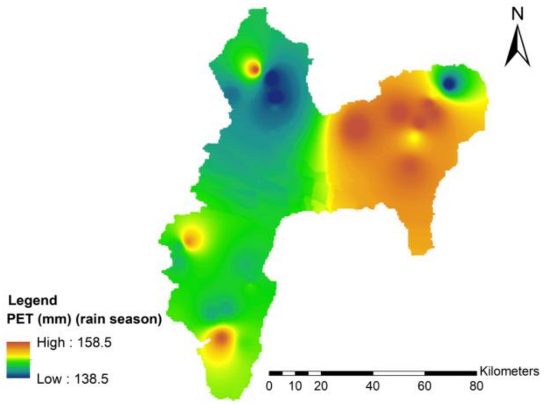
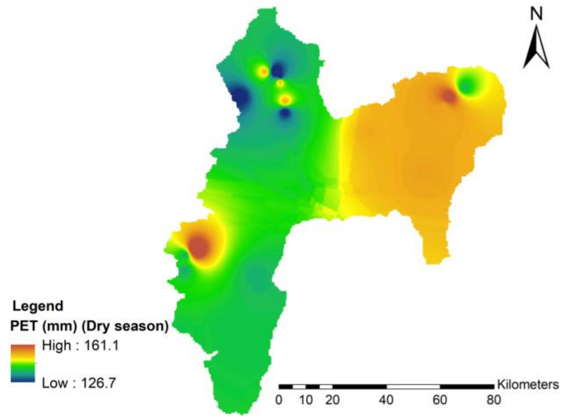
APPENDICES

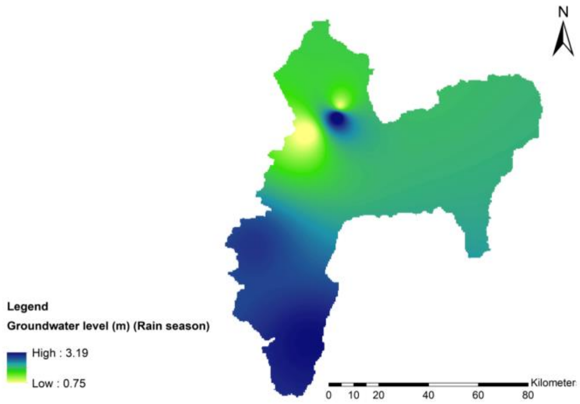
Appendix 1: Rainfall, temperature and wind speed of the catchment

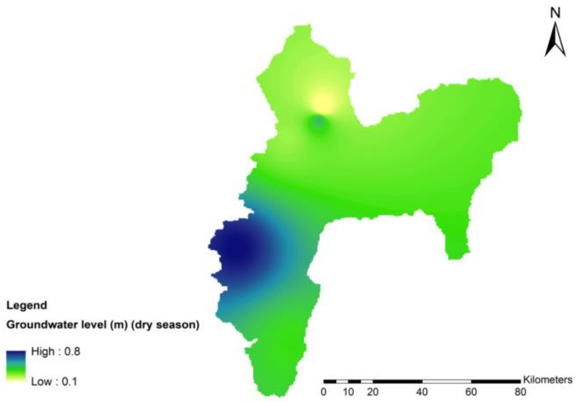


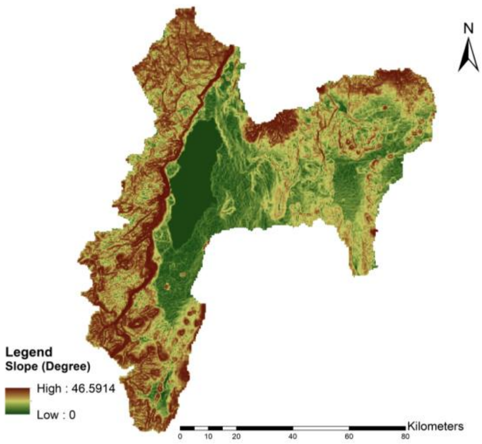
Appendix 2: Hydro meteorological parameter, elevation and slope

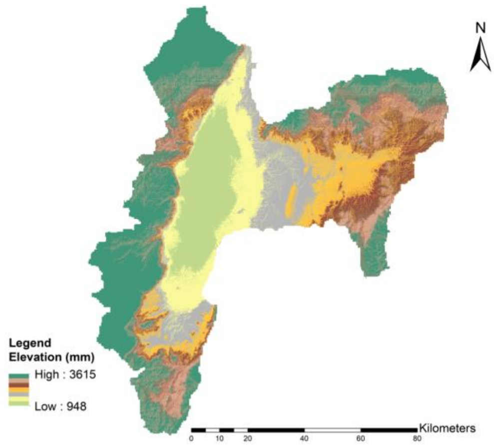




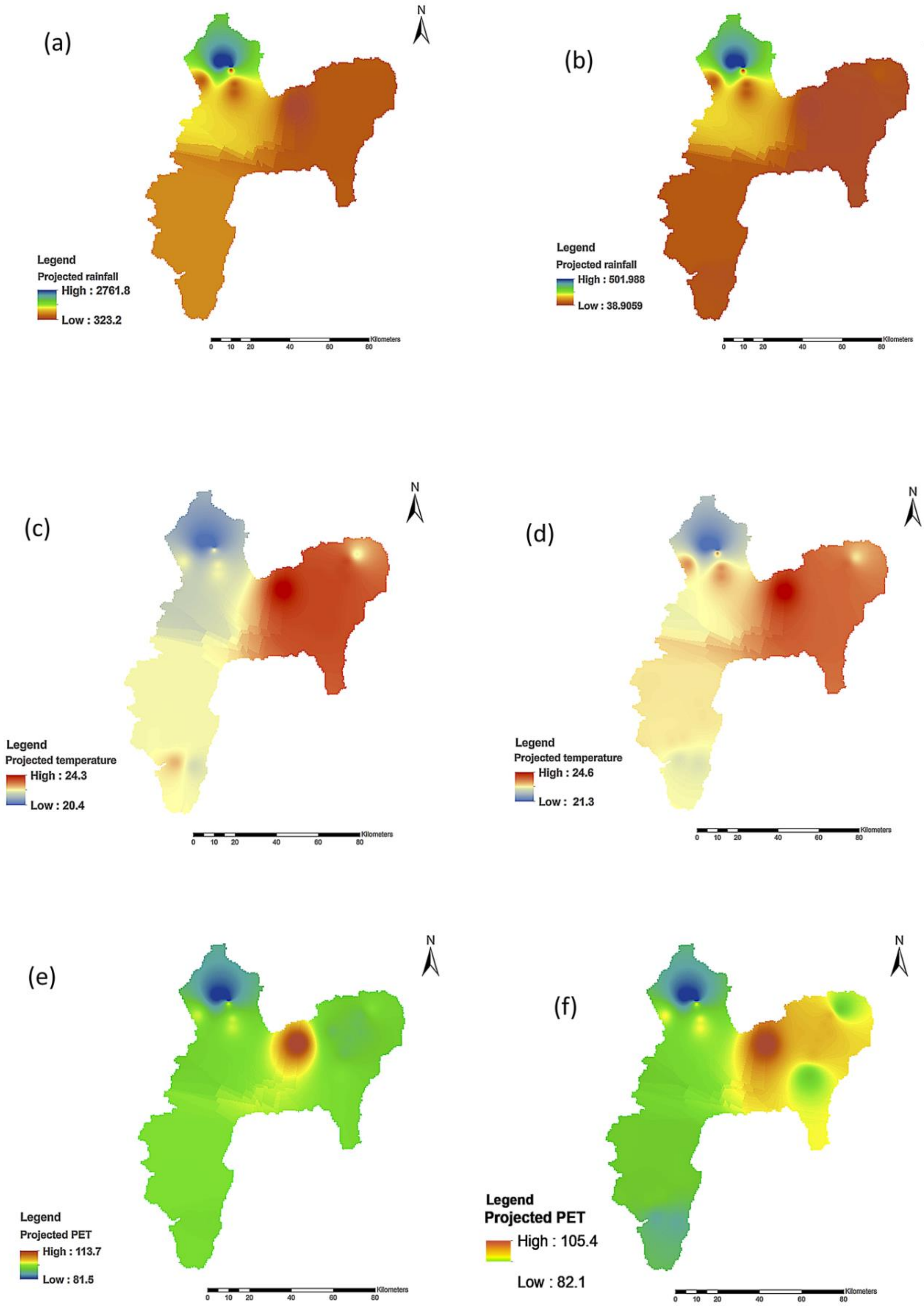




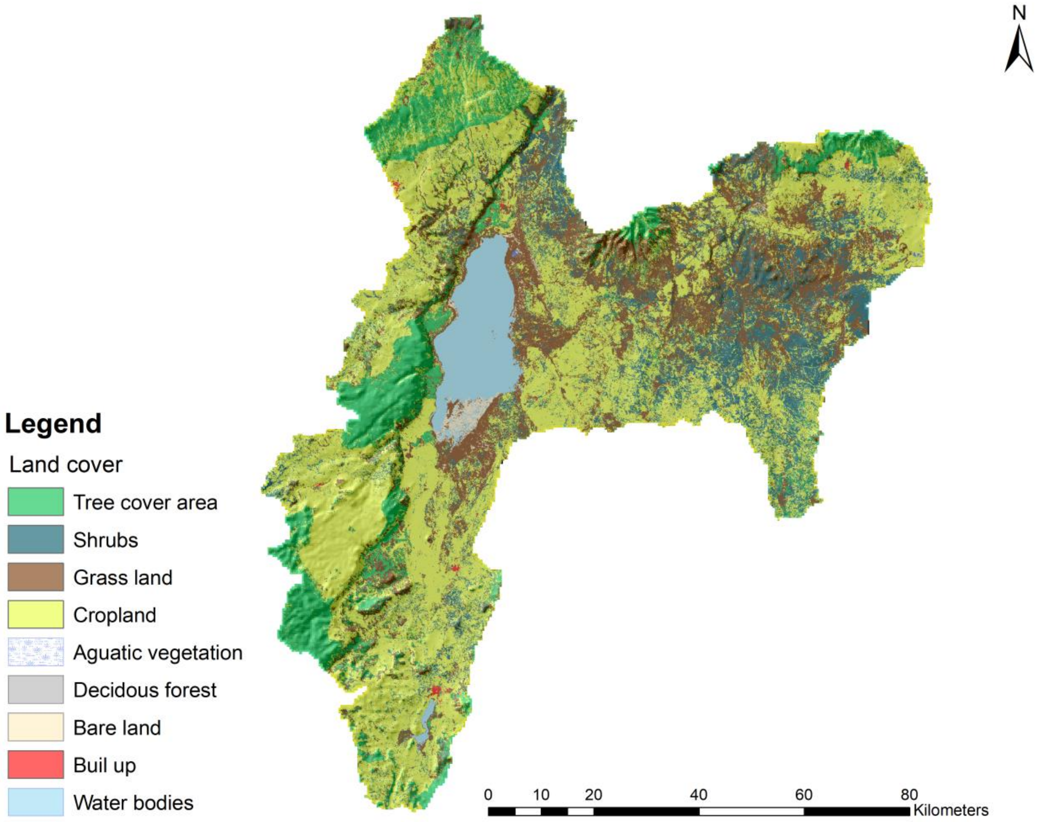




Appendix 3: Climatic projection inputs of (a) rainfall in rainy season (b) rainfall in dry season (c) temperature in rainy season (d) temperature in dry season (e) PET in the rainy season (f) PET dry season



Appendix 4: Spatial distribution of land use/cover in Lake Manyara catchment correct legend built up



Appendix 5: Spatial distribution of soil type in Lake Manyara catchment